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No. 21. 1959 November

THE PHOTOGRAPHIC ZENITH TUBE OF THE ROYAL GREENWICH OBSERVATORY

D. S. Perfect

The Photographic Zenith Tube (P.Z.T.) is primarily intended for use as a transit instrument to improve the accuracy of time-determination. It is also used for measuring variations of latitude. Its range is limited to stars in a small region of the sky, but this drawback is offset by the superior accuracy of the measurements.

The chief difficulty with the normal type of transit instrument is to set the telescope (Fig. 1 (*a*)) (or more precisely its line of sight defined by the nodal point N and the fiducial mark X) in the meridian with sufficient accuracy; or alternatively to assess accurately the error which exists after an attempt to set it has been made. If one is observing in the zenith at the latitude of Herstmonceux an angular displacement of the telescope by 10 seconds of arc from the meridian will produce an error of 1 second in time.

At the beginning of this century the accuracy expected in time-determination was about one tenth of a second. The equivalent accuracy in the direction of the telescope was thus one second of arc. Even this was not easy to achieve with the normal type of transit instrument. Improvement was obtained by two changes of technique: firstly by the introduction of the impersonal micrometer, and secondly by the use of a small reversible instrument. But the transit instrument has been fighting a losing battle, for owing to a variety of causes—the growth of new demands for more accurate time, and the great improvement in clock performance which has fulfilled one of the necessary conditions of such accuracy—the standard has been increased by a factor of about 100; and it is now both relevant and desirable to check the clocks by astronomical observation to the accuracy of a millisecond. The equivalent accuracy in the direction of the telescope is about $0''\cdot01$ of arc. To attain this by means of the classical type of transit instrument is practically impossible. For this there are two reasons, (1) mechanical imperfection and (2) inadequacy of criterion.

A transit instrument intended for use over a wide range of the meridian must be provided with means of changing the elevation of the telescope in order that one may set on any point in this range. For this purpose the telescope is constrained by the mechanical system of two pivots resting in fixed Vs with the intention of permitting its rotation about a fixed axis π—which is (by adjustment of the Vs) to be set nominally horizontal and E–W (Fig. 1 (*a*)).

But the function of this constraint is not merely to provide facility for changing elevation. On it depends entirely our assumed knowledge of the position of the telescope relative to any selected point of the meridian, and the consequent transit time we attribute to a star which crosses at that point.

If the mechanism itself is perfect—that is if the surfaces of the pivots are segments of the same cylinder, and if the movable system of telescope and pivots and also the supports of the Vs have perfect rigidity—then the pivots will define a

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But the function of this constraint is not merely to provide facility for changing elevation. On it depends entirely our assumed knowledge of the position of the telescope relative to any selected point of the meridian, and the consequent transit time we attribute to a star which crosses at that point.

If the mechanism itself is perfect—that is if the surfaces of the pivots are segments of the same cylinder, and if the movable system of telescope and pivots and also the supports of the Vs have perfect rigidity—then the pivots will define a

fixed axis of rotation π, and the line of collimation NO (Fig. 1 (*a*)), at right angles to π, will describe a plane. Apparent transit time is the time when the star is in this plane (or when its image is at O in the focal plane); to derive the true transit time from this apparent time we must determine the orientational departure of π from the horizontal E–W line.

Rotation about π is not, however, the only motion provided for the telescope. O (the instrumental zero point of the focal plane) can only be derived from its relation to the physically defined point X; this can be done by reversing π through 180°, and thus bringing X to X′ at an equal distance on the other side of O (Fig. 1 (*b*)).

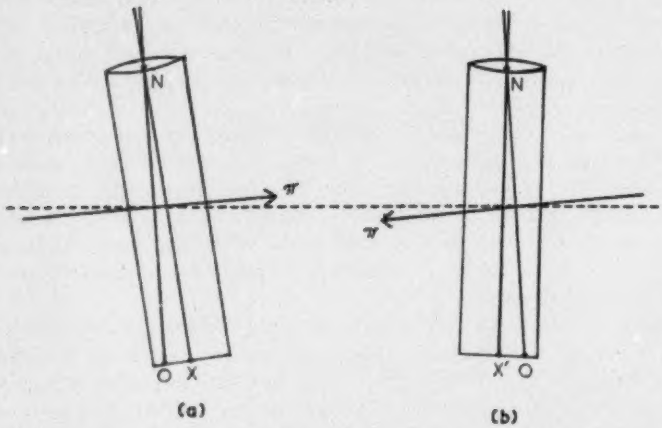


FIG. 1.—*The transit instrument. N is the nodal point of the O.G. and X is a fiducial mark. The dotted line represents the horizontal east-west direction. π is the axis of rotation, nominally E–W and level, but in practice not exactly so. The line of collimation NO is in the plane through N perpendicular to π. OX is the focal plane. NX′ is the position of NX after reversal of π through 180°.*

It is now the normal practice in time-work thus to make a direct determination of the point O for each transit, in order to eliminate the effect of secular changes in the inclination of NX. The procedure is to make OX large enough to observe the star image at X before transit, to allow time for reversal, and to reobserve the image at X′. In practice the reversal of π is carried out in two stages—purely as a matter of convenience in respect of the reversing mechanism. The pivots are picked up, reversed about a vertical axis, and relocated in the Vs. This nominally gives the required 180° rotation of π. In addition to this, a rotation of the telescope about π through twice the zenith distance of the star is required in order to reset on the star. It is, however, simpler kinematically, and relevant to the subsequent development, to assume that the reversal is carried out by a single rotation: namely about NO as axis (Figs. 1 (*a*) and 1 (*b*)).

Now the fundamental assumptions that have been made in deriving transit-time by an instrument of the supposedly ideal behaviour are vitiated beyond present endurance by the imperfection of pivots and unrigidity of Vs which exist in the real instrument. As a result of these imperfections, firstly there is no fixed axis of rotation π by measuring the orientation of which we can deduce the position of the telescope relative to the meridian, and secondly the interchange of pivots in the Vs will not effect a reversal through 180°.

Now the normal separation of pivots in a reversible transit instrument is about 20 inches; so that pivot errors of only one millionth of an inch suffice to deflect the telescope by $0''\cdot01$ of arc, and a temperature difference of less than $1/100\,^{\circ}$C in the supports of the Vs of a small transit instrument suffices to produce a like deflection. There is no need to emphasize the difficulty of producing and testing pivots to this order of accuracy; nor the improbability that, however good they are initially, the pivots will for long remain effectively unchanged by wear. Nor, as regards rigidity, is there need to enumerate the many other causes that may produce such small deflections. The mechanism cannot in fact be made good enough.

Even if there were no intrinsic instrumental errors, the attempt to derive transit time to this high accuracy fails for the lack of a good enough criterion in measuring the departure of the orientation of π from true E–W and level. The azimuth component can only be determined by stellar observations. We need not consider the accuracy attainable, since (even if it were perfect) the level component remains as a limiting factor. The level is measured either by spirit-level or by autocollimation on a mercury reflector. But the limit of accuracy of both these methods is of the order of $1/10''$ of arc instead of the required $1/100''$ of arc. This fact alone is a sufficient cause of defeat.

But there is an additional cause: the practical application of either of these methods involves the use of the pivots; therefore the fidelity of the criteria, even if their precision were adequate, is vitiated by pivot errors: for the autocollimation method cannot be applied in the observing position but only in the nadir, and measurement in the nadir is not pertinent after the telescope has been rotated about faulty pivots to point to the star. And although a spirit level of the hanging type can be applied to the pivots in the observing position, its indications are themselves independently affected by pivot errors.

It is clear therefore that a radical change of instrumental technique is required, if there is to be any hope of reaching the desired accuracy.

Some of the difficulties cited are immediately overcome if, instead of working over a wide range of the meridian, we restrict observation to the close neighbourhood of any particular point of it. For in this case there is no need to change the elevation of the telescope to set on different stars; therefore we can arrange to carry out reversal by rotation about the axis NO (so eliminating the need of the rotation through twice the zenith distance) and the axis of rotation, π, becomes superfluous. The pivots and their errors can thus be eliminated entirely. The only motion now required is reversal through 180° about any axis approximately parallel to the optic axis.

The instrument may therefore be reconstructed as shown in Fig. 2 (*a*). Here the telescope is located kinematically on, and can be reversed on, a fixed plane table which is to be tilted so that its normal is directed to the selected point of the meridian. The instrumental zero point O (defined by the axis of reversal ρ) lies on the normal to the table through N. If we provisionally ignore imperfection of constraint, the only problem now is to measure the orientation of this axis relative to the meridian. In the general case this problem cannot be solved; in a particular case it can, namely when the selected point of the meridian is the zenith, for in this case the selected point is defined by gravity only.

The supporting table must now be level, and the axis ρ vertical, as in Fig. 2 (*b*); this is a condition which we can test by a single and purely physical criterion. And, moreover, because this criterion can now be applied with fidelity in the observing

A 2

position it follows that imperfection of constraint is in fact unimportant. Now that the selected point is the zenith we can attach a spirit level permanently to the telescope itself and it will give a proper criterion even if the table is not perfectly flat or rigid, because the mean of its readings for the initial and final positions of the telescope measures the tilt of the effective axis of reversal without reference to any wobbles of the instantaneous axis. There is indeed only one essential mechanical

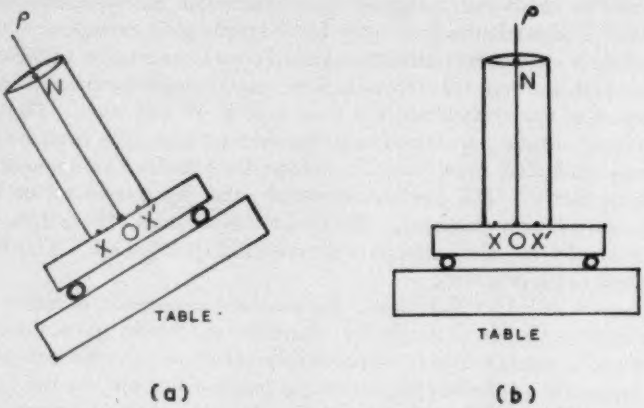


FIG. 2.—*The telescope is reversible on a fixed plane table. ρ is the axis of reversal. N is the nodal point of the O.G. and the instrumental zero point O, defined by ρ, lies on the normal to the table through N. (a) shows the general case of the telescope pointing to an arbitrary point of the meridian. In (b) the telescope points to the zenith; the axis ρ must be vertical to an accuracy of* $0''\cdot01$.

condition to be fulfilled in this system: namely, effective rigidity of the moving telescope for the comparatively brief period of a transit observation, say for two minutes; because of the constancy of posture this is fairly easy to achieve. Thus by restriction of observation to the zenith the problem has been reduced to that of adequacy of criterion only.

Two criteria are needed:

1. For the departure of reversal angle from 180°; this is only required because we must in practice observe slightly away from the zenith.

2. For the tilt of the effective axis of reversal. The first is not critical. Departure from 180° is equivalent to an azimuth error of the Vs of an ordinary transit instrument of half the amount; its effect vanishes in the zenith; and at a Z.D. of 15′ (the maximum used in the Herstmonceux P.Z.T.) the reversal error must exceed 4″ of arc to become significant. It is easy to control (or measure) to this accuracy. But the second criterion is critical (to 1/100″ of arc); and the scheme is defeated at this point simply because the spirit level is not good enough.

Instead, however, of trying to improve on the spirit level (which would be possible but difficult), we follow Airy in an entirely different approach, which leads us straight to a complete solution. There are two distinct steps: the first purely optical, the second purely mechanical. Suppose as in Fig. 3 we insert in the convergent beam from the lens, and halfway down to the focus, a fixed plane mirror M, so that the optical path is folded up and the focal plane is brought up

into coincidence with the nodal plane (XY). It is obvious that the instrumental zero point O (defined by ρ) will now coincide with the same point of the focal plane, namely N, whatever the direction of the axis of reversal ρ may be. Thus by taking this step we cease to be concerned with anything to do with the tilt of ρ, including a criterion for it. Interest is now transferred to M which has entirely supplanted ρ in determining what point of the sky is imaged at O. If M can be adjusted exactly level, this point of the sky will be the zenith. But if M has a level error, as shown in Fig. 3, the zenith point, Z, of the focal plane, will be displaced from O by an amount which must be determined to $1/100''$ of arc. Such a determination would be no

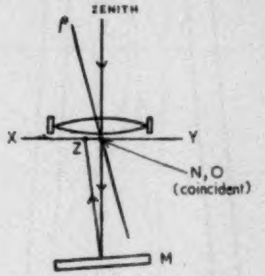


FIG. 3.—*The plane mirror M is below the O.G. so that the plane XY is the nodal plane and the focal plane. The nodal point N and instrumental zero point O coincide whatever the tilt of the axis of reversal ρ. Z is the image of the zenith point. If M is replaced by a mercury bath Z will coincide with O.*

less formidable than the similar determination for ρ from which the optical folding has given us an escape. But because we have elected to work in the zenith the determination can be avoided altogether by taking the mechanical step of making M a mercury reflector. Thus the need of an independent spirit or other type of level vanishes; M becomes its own perfect level, and Z now coincides with O with sensibly perfect accuracy.

The system we have thus arrived at is precisely that of the P.Z.T., except for the minor technical change of replacing the visible fiducial mark X by a photographic plate. This is done to remove the personal errors (which are not completely avoidable even by the use of the impersonal micrometer) from the domain of direct stellar observation to the domain of a measuring machine, where measurement of an objective record can be made or repeated at leisure.

The general arrangement of the instrument itself is shown in Fig. 4. The telescope proper, comprising the lens L and photographic plate P is now called the "rotary". In virtue of the folding up it has been compressed to quite short axial length. (This incidentally increases the rigidity and facilitates the mechanical arrangements for reversal.) The focal length, however, on which sensitivity depends, remains long, and is indeed made longer than usual, since flexural troubles are absent. It is $3\frac{1}{2}$ m as compared with 1 m for the small transit instrument, and this gives a scale value of $1'$ per mm. The table, for supporting and locating the rotary, is in the form of a conical tube T which rests on a concrete pier. The mercury reflector is mounted on a separate pier bedded in sand.

As we have seen, the constraints of the rotary are not critical. It is reversed on a ball race to minimise friction, and is turned by a system of steel cables that are

pulled by solenoids. The reversal is controlled well within the tolerance of 4″ of arc (quoted earlier) by two pairs of stops. Bumping on the stops (which might destroy the rigidity as well as the stops) is prevented by oil damping. The actual reversal angle is determined by autocollimation. All these features of the instrument are new.

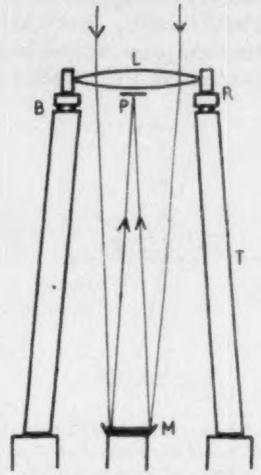


FIG. 4.—*General arrangement of Photographic Zenith Tube. The O.G. (L) is mounted on the rotary R. M is the mercury bath, P is the photographic plate and T the conical tube supporting the rotary, which turns on the ball race B.*

The method of recording is essentially that of the impersonal micrometer. But, as there is no visual criterion, no attempt is made to secure exact and detailed following of the stellar image: the plate carriage is simply traversed at uniform speed. An exposure time of 20 sec is allowed in order to secure records down to magnitude 9·5. A pre-transit exposure is given which results in the production of a point record on the plate. The carriage (and thence the star-image) is timed during the exposure. The rotary is then reversed, and a similar post-transit exposure is made.

Let t_1, t_2 (Fig. 5) be the mid-exposure times (which correspond to the same relative position of plate and O.G.). Reversal carries the pre-transit dot round a semi-circle of centre Z to I_1. If the carriage could have been started correctly for the second traverse (so that t_1, t_2 were symmetrical about transit time), the line I_1I_2 would be parallel to the meridian. But in general we have an R.A. staggering of I_2 relative to I_1.

If v is the speed of the star image, then

$$t_1 = t_m - \frac{x_1}{v}$$

$$t_2 = t_m + \frac{x_2}{v}$$

or

$$t_m = \tfrac{1}{2}(t_1 + t_2) - \tfrac{1}{2}\frac{(x_2 - x_1)}{v}.$$

To measure $x_2 - x_1$ we must know the E–W direction on the plate. To determine this, and also the speed v, we repeat the process with another similar pair of exposures taken when the star is closer to the meridian: at times t'_1, t'_2 (Fig. 5). This pair is inverted with respect to the first as regards rotary orientation; i.e. the rotary is reversed between each successive exposure in the set of four (this is done to produce maximum R.A. separation of dots for getting the best determination of v).

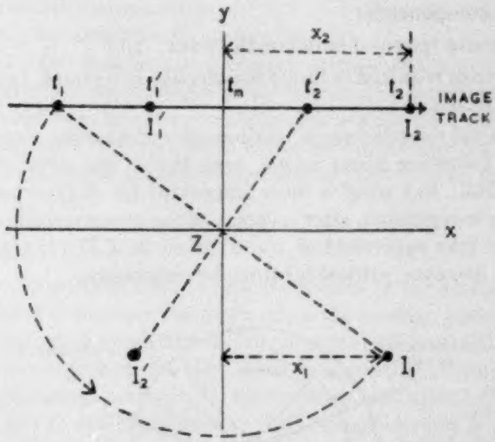


FIG. 5.—*The photographic record. The x axis is the projection of the prime vertical, the y axis that of the meridian. The star image moves along the track, its position at the four times* t_1, t_1', t_2', t_2 *being as shown.* t_m *is the time of meridian transit. The rotary photographic plate is reversed between each exposure and the subsequent one. After the fourth exposure, the four images on the plate are situated at* I_1, I_1', I_2' *and* I_2. *The perpendicular distance between the lines* I_1I_2' *and* $I_1'I_2$ *is a measure of twice the meridian zenith distance of the star. The scale value of the plate is obtained from the distances* I_1I_2' *or* $I_1'I_2$ *and the observed times. The slight curvature of the image track is not shown in the diagram.*

Thus the final picture on the plate is a nearly rectangular array of four dots, I_1, I_1', I_2, I_2'. The perpendicular distance between the lines I_1I_2' and $I_1'I_2$ is a measure of twice the meridian zenith distance of the star. The scale value of the plate may be obtained from the distances I_1I_2' or $I_1'I_2$ and the observed times.

It has been noted that positional errors of the telescope (or rotary) as a whole are not critical; but that the critical mechanical condition is relative rigidity of the essential components, i.e. lens and plate. The introduction of a moving plate-carriage of course violates this condition; and the motion must therefore be critically defined to make it permissible. The chief difficulties of mechanical design thus pertain to the constraint of the plate-carriage. The other two crucial features of the instrument are also related to the carriage. We consider the three briefly: They are (1) carriage design; (2) carriage constraint; and (3) carriage timing.

1. *Carriage design*

The carriage in Ross's P.Z.T. was small, and was located in the centre of the lens aperture. It ran on guiding rails and was driven by a screw. All of these intruded on the aperture, and together constituted an asymmetrical obstruction

which, owing to diffraction, produce asymmetry of the stellar images. In the Herstmonceux P.Z.T. (Fig. 6) the main frame of the carriage is removed from the aperture by making it annular and external to the aperture. This solves the whole problem, since the constraints and drive can thus also be made external. The only obstruction is from the plate holder and its supports, which are easily made symmetrical.

2. *Carriage constraint*

This has two components:

(*a*) the constraint required to define the track; and

(*b*) the constraint required to locate the carriage in its track, i.e. the mechanism of driving the carriage.

(*a*) The nominal requirement is rectilinearity of traverse, since this is the best compromise for following a star image, both before and after reversal, over its slightly curved trail. But what is more important for Z.D. measurements than true rectilinearity is repetition, after reversal, of the pre-reversal track. The tolerance of departure (the equivalent of 1/100″ of arc in Z.D.) is 1/3 micron. This departure is not, however, critical for time determination.

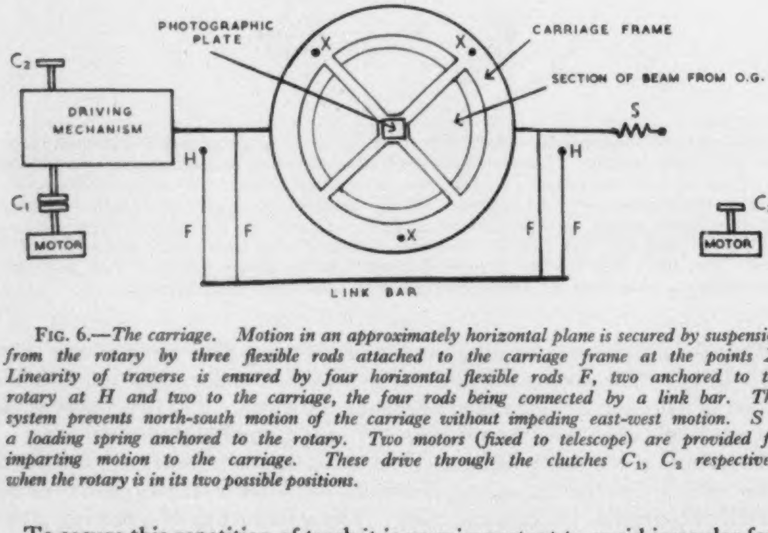


FIG. 6.—*The carriage. Motion in an approximately horizontal plane is secured by suspension from the rotary by three flexible rods attached to the carriage frame at the points X. Linearity of traverse is ensured by four horizontal flexible rods F, two anchored to the rotary at H and two to the carriage, the four rods being connected by a link bar. This system prevents north-south motion of the carriage without impeding east-west motion. S is a loading spring anchored to the rotary. Two motors (fixed to telescope) are provided for imparting motion to the carriage. These drive through the clutches C_1, C_2 respectively when the rotary is in its two possible positions.*

To secure this repetition of track it is very important to avoid irregular forces such as friction, and the uncertainties of location involved in a rolling constraint. The avoidance of irregular frictional forces is also an important condition of securing the uniformity of motion along the track which is needed for time-determination. All the carriage constraints of the Herstmonceux P.Z.T. have therefore been made elastic.

Motion approximately in a horizontal plane is secured by suspension from three flexible vertical rods. Rectilinearity of traverse in this plane is secured by four horizontal flexible rods. All four are attached to a free bar at one end, and two to the carriage and two to the rotary at the other end. The bar moves at half the

speed of the carriage, and the resultant N–S displacement of the carriage is zero. The system is compensatory for thermal expansion. A further merit of this system is complete absence of wear.

(*b*) Irregularity of the carriage drive produces negligible direct error in Z.D. Its chief importance is with respect to time determination. Here the tolerance for departure from repetition is again 1/3 micron.

The driving system is also shown in Fig. 6. A synchronous motor is used to drive in succession:

a worm gear which drives a screw;

a nut which is traversed by the screw; and

a differential roller system which imparts motion to the carriage by means of steel tape. Successive smoothing of irregularities is thus secured.

It may be noted that the carriage constraints and drive are mutually accommodating: the tape exerts no erratic N–S forces on the carriage which might disturb its track, and the elastic constraints of the carriage introduce no erratic disturbance of the driving system.

3. *Carriage timing*

Fig. 7 shows the method used to time the motion of the carriage. The normal way of doing this is to measure the times when the carriage passes specified points of its track. Contacts are operated in a supposedly definite relation to the carriage motion, and cause signals to be sent to an independent chronograph on which clock signals are also recorded. If the contacts are operated by the carriage itself the precision is not high because the carriage-motion is slow. But if, to increase precision, magnification is introduced by operating the contacts from faster-moving components of the driving system, accuracy is impaired owing to uncertainty and irregularity of linkage between drive and carriage. The chronograph must of course have millisecond accuracy for both carriage and clock signals.

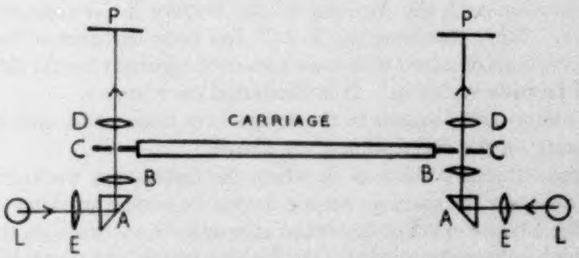


FIG. 7.—*The chronographic system. Flashing lamps L send pencils of light through the pinholes C on to photographic plates P. The lamps L are fixed to the telescope tube. The collimating lenses E, the projecting lenses D and the plates P are fixed to the rotary. The prisms A and the condensing lenses B are fixed to the carriage.*

In the Herstmonceux P.Z.T. a different method is used. Instead of determining when the carriage is at specified points of its track, we determine where it is at specified times. This has great advantages:—

1. The times are not controlled by contacts but by a method which easily achieves millisecond accuracy.

2. The independent chronograph is eliminated.

3. In recording the positions of the carriage, purely optical magnification, which has no uncertainty of linkage, can be used.

4. The times (unlike the contacts) can be spaced at exactly equal intervals so that the record of the corresponding carriage positions can be used to test the uniformity of traverse.

5. The record can also be used to test for repetition of track.

A pin hole of 10μ diameter is attached to the carriage, and every two seconds is illuminated for a few microseconds by a flashing lamp. The times of flashing are controlled well within millisecond accuracy by the standard clock (the error of which is in question). With a magnification of $\times 5$ an image of the pin hole is focused by a micro-projector on a horizontal photographic plate attached to the rotary. A uniform traverse is thus recorded as an equally spaced series of dots. Using the time scales (given by the dots) for two corresponding traverses we can find (by interpolation) the required times t_1, t_2 when the carriage passes any specified point of its track.

The guiding principle throughout the design has been to try to keep the individual errors that arise from any one cause within the equivalent of 1 ms. It is expected that this P.Z.T. will produce a substantial increase in the accuracy of the Greenwich time determinations. That this is not unlikely is suggested by comparison of the results obtained for a night's work with the Bamberg instrument at Abinger and with the United States P.Z.T.s.: the ratio of the mean absolute deviations being of the order of 10.

To what extent this difference is due to purely instrumental causes is not known; it is hard to say what further improvement may still be hoped for when the new P.Z.T. is brought into use, or how near we may be to limits imposed by the atmosphere.

Postscript.—This article was prepared for presentation to a Colloquium held in connection with the Meeting of the Society in Newcastle-on-Tyne on 1953 July 21. Since that time the P.Z.T. has been installed at Herstmonceux and the observations obtained with it are now used regularly for the determinations of time and latitude variation. It is illustrated on Plate 22.

Several minor modifications to the design have been made, only one of which has any bearing on the description given above.

Under the arduous conditions in which the instrument works, it was found difficult to maintain the carriage timing device in perfect working order, partly because of the adverse effect of deposited atmospheric moisture on the insulation of the very high voltages required for the flashing lamps, and partly because of the unreliability of these lamps. The makers therefore designed a mechanical contact system which gives adequate accuracy. This was fitted and now replaces the carriage timing system described in the last section.

With the experience gained it is now possible to quote reliable figures for the accuracy attained in practice under working conditions. Assigning a weight of unity to the result of the observation of a single star whose zenith distance is zero, the probable error of unit weight deduced from the internal accordance of the measures of the photographic images is, in the mean, $\pm 0\cdot07$ seconds of arc in both co-ordinates ($\pm 0^{s}\cdot007$ in time).

This is the probable error calculated from the internal accordance of the measures and therefore includes only those uncertainties due to short-term atmospheric disturbances, photographic distortion, errors of measurement and instrumental causes. It does not include any residual error in the adopted star places nor long-term atmospheric refraction anomalies. The probable error of a typical night's work, including the latter uncertainties, calculated from the external agreement of the results is $\pm 0''\cdot 03$ (or $0^s\cdot 003$ in time).

Royal Greenwich Observatory,
Herstmonceux Castle,
Hailsham, Sussex:
1958 *April* 10.

PECULIAR STARS

R. H. Garstang

"Tut, tut, child," said the Duchess. "Everything's got a moral if only you can find it."

—Lewis Carroll, *Alice in Wonderland*, Ch. 9.

Introduction

It is one of the fundamental cornerstones of astronomy that the majority of the stars can be classified into a few basic sequences of types. The most important of these is the main sequence, stretching in the Hertzsprung–Russell Diagram from O stars of absolute visual magnitude -4 through B, A, F, G and K to M stars fainter than absolute magnitude $+10$. Stars of the main sequence are generally known also as dwarfs. A second sequence is the giant sequence, comprising stars of absolute magnitudes between about -1 and $+1$, and stretching from spectral type G8 through type K into type M. In addition to the giants and dwarfs there are a number of supergiants which may for the present purpose be regarded as normal stars. There is a small proportion of the stars which cannot be classified into dwarfs, giants or supergiants, and such stars we regard as peculiar stars. Stars are at the present time not regarded as peculiar merely because they happen to be of an unusual size or have an unusual surface temperature; they must have an unusual chemical composition, show unexpected emission lines, have some kind of variability or be associated with other stars or with nebulae in a peculiar way. The existence of peculiar stars was first realized by the Harvard astronomers, especially by Miss Maury. It was found that not all the stars fitted into one sequence (the main sequence). At a later date the existence of giant and supergiant stars was discovered, and as our knowledge of astrophysics developed it was shown that many of the peculiar stars which had been discovered were giants and supergiants. Their spectroscopic peculiarities could be explained in terms of their sizes, correspondingly lower atmospheric pressures, and lower surface temperatures compared with approximately similar dwarf stars. These are not now regarded as peculiar. All this is considered independently of any evolutionary processes which may turn main sequence stars into giants and supergiants, provided that these processes have not affected the stellar spectrum otherwise than through variations in the temperature and pressure of the atmosphere of the star.

Types of Peculiar Stars

When full allowance has been made for the effects of atmospheric temperatures and pressures there remain an appreciable number of stars which must be regarded as peculiar. Table I contains a classification of most types of peculiar stars. There is one important problem in the classification which deserves some discussion at the outset. A number of stars of high velocity—giants, subdwarfs, and others—have long been known to exhibit peculiarities. In recent years these stars have been shown to be members of Baade's Population II, and from the point of view of Stellar Populations they should be regarded not as peculiar stars but as normal stars of Population II. It now appears probable that there exists

TABLE I

Classification of peculiar stars

Group	Type	Example
I	Wolf–Rayet stars	
	(a) Carbon sequence	HD 192103
	(b) Nitrogen sequence	HD 151932
II	Emission-line stars	
	(a) Of stars	9 Sagittae
	(b) P Cygni stars	P Cygni
	(c) Be stars	χ Ophiuchi
III	Shell stars	ζ Tauri
IV	Peculiar A stars	
	(a) Peculiar A stars	HD 125248
	(b) Metallic line stars	63 Tauri
V	White dwarfs	Sirius B
VI	Carbon stars	Y Canum Venaticorum
VII	S stars	π^1 Gruis
VIII	Symbiotic stars	CI Cygni
IX	Hydrogen-poor stars	HD 124448
X	Pulsating stars	
	(a) Classical cepheids	δ Cephei
	(b) Long-period variables	o Ceti
	(c) β Canis Majoris stars	12 Lacertae
	(d) Semi-regulars and others	RV Tauri
XI	Exploding stars	
XII	Miscellaneous	
	(a) Carbon-poor stars	HR 885
	(b) Lithium stars	WZ Cassiopeiae
	(c) Intermediate-carbon stars	GP Orionis
	(d) Ba II stars	ζ Capricorni
XIII	Stars not intrinsically peculiar	
	(a) Binary systems	RW Tauri
	(b) T Tauri stars	T Tauri
	(c) Interacting with nebulosity	SU Aurigae
XIV	Population II stars	
	(a) G-K giants	δ Leporis
	(b) Carbon stars (CH stars)	HD 201626
	(c) Subdwarfs	HD 140283
	(d) Faint blue stars	$+28°$ 4211
	(e) Cluster cepheids	RR Lyrae
	(f) Long-period cepheids	W Virginis

a continuous range of stars and stellar spectra from extreme Population I to extreme Population II. We should therefore regard normal stars as including variations of Population as well as of atmospheric temperature and pressure. Our knowledge of Population II stars is in its infancy (this may apply to Population I as well!); it is still convenient to regard Population II stars as peculiar relative to the conventional normal stars of Population I and they are separately listed as such in Table I.

I. Wolf–Rayet Stars

These strange stars were discovered by Wolf and Rayet in 1867; about 100 are now known, the apparently brightest being γ Velorum. They are present in some spectroscopic binaries and eclipsing variables. Some are probably

members of young clusters, associations and aggregates of stars. The nuclei of planetary nebulae, though probably not Wolf–Rayet stars, show many similar spectral features. They are distinguished spectroscopically by the emission bands of very great width which are present in their spectra; these widths

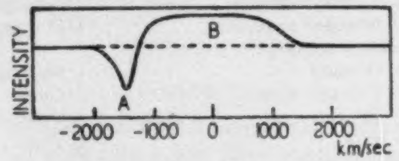


FIG. 1.—*Profile of the line λ 3889 of He* I *in the Wolf–Rayet nitrogen sequence star HD* 192163. *Note the absorption A on the violet (negative velocity) edge of the broad emission feature B.* (*Adapted from C. S. Beals*, Pub. Dom. Ap. Obs., **6**, 95, 1934.)

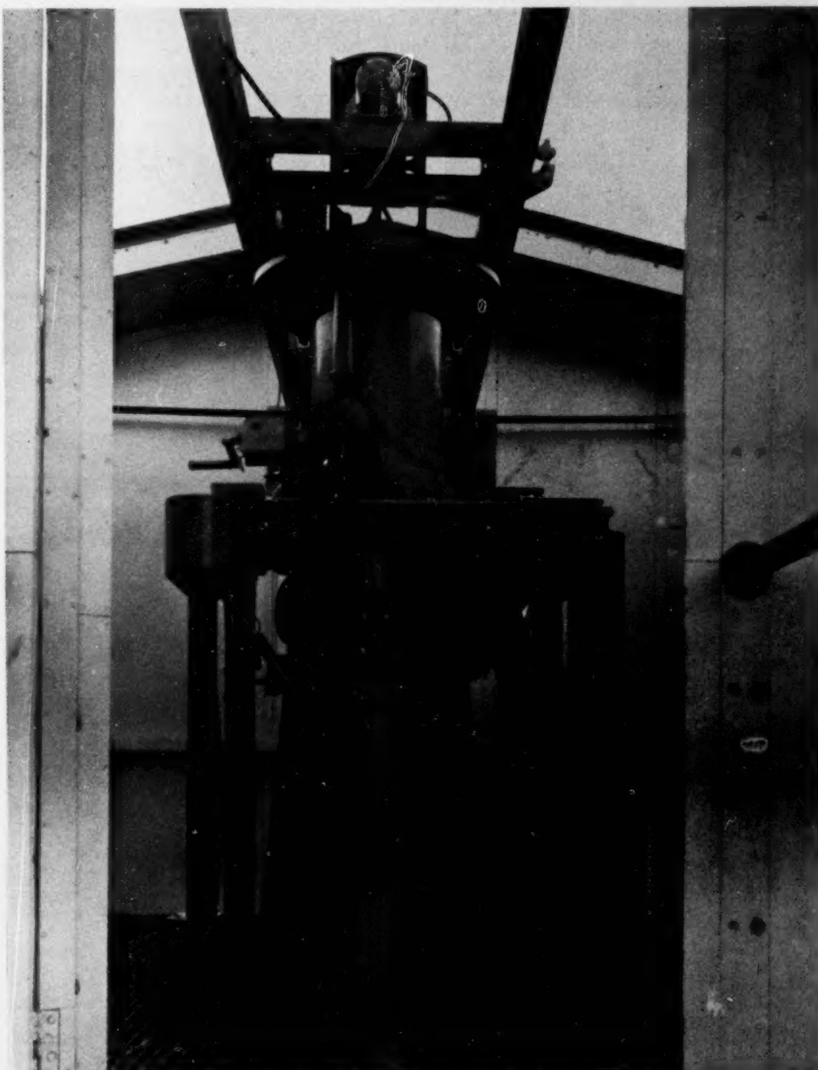
may be as much as 100 A. A typical line profile is shown in Fig. 1. Many of these bands have absorption on their violet edges. Most Wolf–Rayet stars fall into one of two classes:

(*a*) carbon sequence, in which bands of several times ionized carbon and oxygen are present in the spectrum but bands of ionized nitrogen are weak or absent;

(*b*) nitrogen sequence, in which bands of several times ionized nitrogen are present and those of carbon and oxygen are weak or absent.

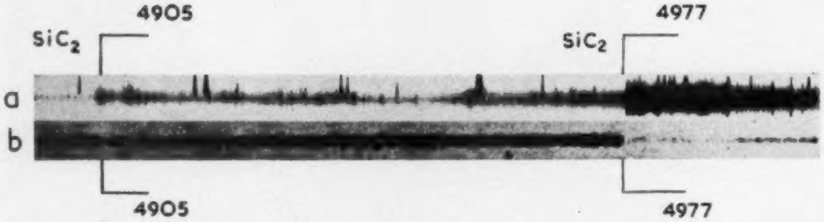
A few are known which combine the features of the two groups. Hydrogen and helium are present in both sequences, hydrogen being relatively weak and He II very strong. The bands of oxygen are due to O III, O IV, O V and O VI, those of nitrogen to N III, N IV and N V and those of carbon to C II, C III and C IV. The widths of the emission bands vary from star to star, and for a given star from atom to atom. The bands requiring higher excitation generally have smaller widths. This suggests that the atmospheres of the Wolf–Rayet stars are stratified. Further, if the widths of the bands are interpreted as due to Doppler effects, an outward acceleration is implied. This led to C. S. Beals' interpretation of Wolf–Rayet stars as stars which are ejecting atoms from their surfaces at high speeds. The absorption at the violet edge of many of the emission bands is explained as absorption by material thrown off by the star and moving in the line of sight (Fig. 2). The temperatures of the Wolf–Rayet stars are very uncertain; values ranging between 7000 °K and 100000 °K have been obtained by various methods. The lack of agreement between the results is probably due chiefly to departures from thermodynamic equilibrium in the Wolf–Rayet atmospheres; the excitation temperatures generally average about 50000 °K. The visual absolute magnitudes range from -1 to -5 and average -4, somewhat fainter than the majority of O stars.

The eclipsing variable V 444 Cygni (HD 193576) has proved to be one of the most interesting stars in the sky and one of crucial importance for the study of Wolf–Rayet stars. Discovered in 1939, it has a period of 4·2 days and consists of a normal B1 star and a Wolf–Rayet nitrogen sequence star classified as WN 5. Detailed studies of the light and velocity curves have been made, and great difficulties have arisen in their interpretation. For example, the primary minimum in the light curve is twice as wide as the secondary minimum. It is hard to see how this could arise from purely geometrical eclipses. There are also difficulties in understanding the velocity curves. The most reasonable

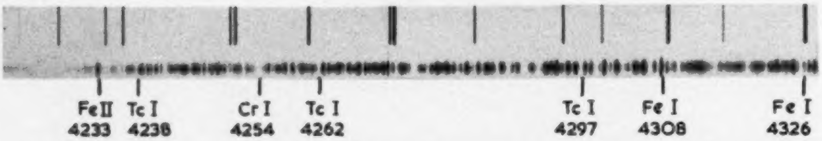


Royal Greenwich Observatory

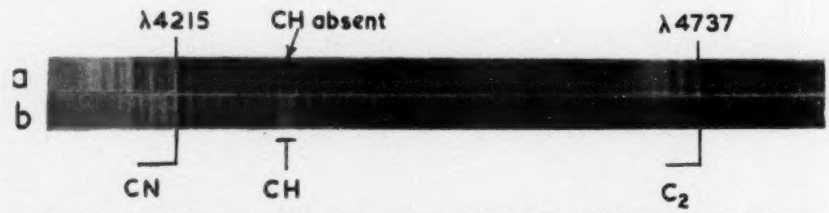
The Photographic Zenith Tube of the Royal Greenwich Observatory. The carriage bearing the photographic plate, and the lens immediately above it, are at about the level of the centre of the photograph. Inside the upper cylindrical part of the tube are the three vertical flexible rods on which the carriage hangs.



A.—*Identification of SiC_2 bands in carbon stars.* Part of the laboratory emission spectrum ascribed to SiC_2 is shown in (a). The corresponding part of the spectrum of the N7 type star VX Andromedae is shown in (b), with two previously unidentified bands at λ 4977 and λ 4905 marked.
(B. Kleman, *Ap. J.*, **123**, 162, 1956.)



B.—*Identification of technetium lines in S stars.* Part of the spectrum of the S type long-period variable star R Andromedae, taken 1944 August 1, 10 days after maximum. The three lines identified in 1952 by P. W. Merrill as due to neutral technetium are marked, together with a few other representative lines. Note the emission lines Fe II λ 4233 and Fe I λ 4308.
(The spectrum is reproduced from P. W. Merrill, *Ap. J.*, **105**, 360, 1947.)



C.—*Hydrogen-poor carbon star.* The hydrogen-poor carbon star HD 182040 (a) compared with the normal carbon star HD 156074 (b). The absence of CH bands in HD 182040 and the presence of strong CN and C_2 bands suggest a real hydrogen deficiency in the atmosphere of this star.
(W. P. Bidelman, *Ap. J.*, **117**, 25, 1953.)

explanation seems to be that the Wolf–Rayet star is surrounded by a large non-luminous atmosphere which absorbs the light of the B1 star when the latter star is behind the atmosphere, but which shows no eclipse effect when the B1 star is in front of the extended atmosphere. This explains the differences in the widths of the light curve minima. Electron densities in the atmosphere ranging from 10^{12} to 10^{9} electrons/cm^3 are required. This explanation is apparently confirmed by the broadening and weakening by electron scattering of the B1 star lines during primary minimum. From the study of HD 193576 the mass of the WN 5 star is 11 $M_{\odot}$, the radius of the core of the WN 5 star 2·1 $R_{\odot}$, and the radius of the WN 5 star envelope 16 $R_{\odot}$. The whole binary system may possibly be surrounded by a diffuse atmosphere.

We see that to explain Wolf–Rayet stars we must have an outwardly moving shell of gas in which the emission lines are formed, and outside this a large non-luminous scattering atmosphere. These gaseous masses will undoubtedly be turbulent, and this can contribute to the problem of atmospheric support. The details of the physical processes involved in the Wolf–Rayet atmospheres are still not understood.

II. Emission-Line Stars

The Wolf–Rayet stars are among the hottest stars known. Coming to those with somewhat lower surface temperatures we find a group of hot peculiar stars which show emission lines in their spectra and which may be subdivided into Of stars, P Cygni stars and Be stars.

(*a*) *Of stars.*—These are a small group of objects which generally resemble ordinary O stars; the O and Of stars form groups which merge into each other. The Of stars have emission lines of He II λ4686 and N III λ4634/40; the symbol f was introduced by the Victoria observers to denote these characteristics. About 13 per cent of all O stars are Of stars. It is not certain whether there is any significant difference in luminosity between normal O stars and the Of stars; there is some evidence that the Of stars are a little brighter, but other types of stars are known in which the presence of emission lines is not a criterion for high luminosity. In addition to the He II and N III lines mentioned, some Of stars show additional emission lines, which may include Hα and C III λ5696. Special physical mechanisms are required to explain the emission lines of He II, C III and N III, for these three lines are the only lines of these elements observed in emission. The He I absorption lines appear normal, suggesting that the outer atmosphere which gives rise to the emission lines cannot extend far from the stellar surface. No forbidden lines have been observed. The emission lines of He II, N III and C III have been found in the spectra of O-type supergiants. Recent work has shown that the emission lines in O and Of stars have extended wings and these may indicate that processes similar to those in Wolf–Rayet stars contribute to the formation of the emission lines.

(*b*) *P Cygni stars.*—The essential feature of P Cygni stars is the presence of one or more emission lines bordered on the violet edge with absorption lines (Figs. 2 and 3). There are in addition all the usual absorption lines occurring in normal O and B stars. P Cygni profiles are usually seen in a few of the hydrogen lines, some helium lines, and sometimes in lines of other elements. The P Cygni line profile may be superposed on an underlying broadened absorption profile (Fig. 3). The P Cygni stars in many ways resemble

Wolf–Rayet stars, and continuous ejection of material has been suggested as the source of the material in which the emission lines are formed. Many of the P Cygni stars are very bright, with visual absolute magnitudes of -7, and even -9. Those of lower luminosity have underlying broadened lines which show that the stars are rapidly rotating, and rotational instability may contribute to the ejection of material.

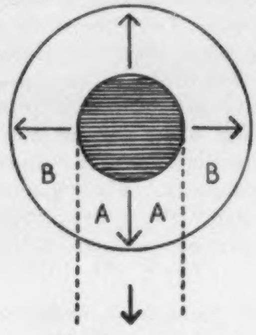


FIG. 2.—*The formation of an absorption edge in stars with expanding atmospheres. The observed emission above the continuum (B in Fig. 1) arises in the regions BB of the atmosphere. The absorption (A in Fig. 1) arises in the region AA when the underlying stellar continuum passes through the expanding atmosphere, the expansion leading to a Doppler shift to the violet relative to the centre of the line.*

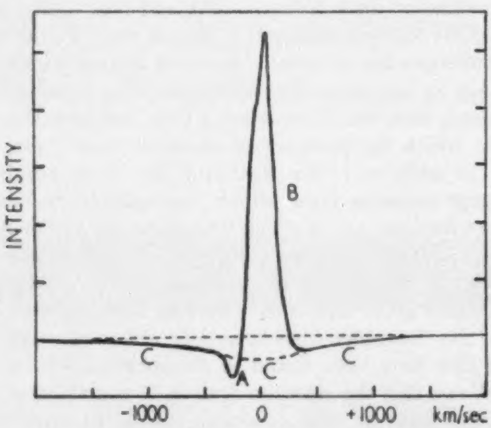


FIG. 3.—*Profile of the Hα line in the P Cygni type star HD 190073. A strong emission line B and a violet-shifted absorption A are superimposed on an underlying greatly broadened stellar absorption line CCC.*

(*Adapted from C. S. Beals,* Pub. Dom. Ap. Obs. **9**, 1, 1951.)

(*c*) *Be stars.*—These stars resemble normal B stars except for the occurrence of emission lines of hydrogen, and occasionally of Fe II and other atoms. There are no forbidden emission lines observed in Be stars. Over 1000 Be stars are now known; their frequency of occurrence is of course much lower than that

of normal B stars. There does not appear to be any significant difference in luminosity between Be and normal B stars. The one important difference, apart from the emission lines, is that the Be stars show much larger rotational velocities even than those shown by normal B stars; in general their spectrum lines are greatly broadened. Rotational surface velocities of up to 500 km/sec have been observed in Be stars. The widths of the emission lines are proportional to their wave-length, and this suggests a Doppler effect broadening. Some Be stars have narrow lines, and these are presumably seen pole-on. Probably the Be stars are rotationally unstable, and have formed or are forming gaseous rings around their equators. The bright lines are probably formed in these rings. These rings may not be stable; changes are observed in the intensities of the emission lines. The hypothesis of gaseous rings is well confirmed by the peculiarities found in certain spectroscopic binaries.

III. Shell Stars

This type of star has been extensively discussed; among brighter examples may be mentioned ζ Tauri, Pleione and 48 Librae. Shell stars occur among types B and A, the shell star of latest type known being 14 Comae, the star being A5 and the shell lines corresponding to about F2. Shell stars show broadened lines of all the usual elements observed in B or A stars. In addition, the hydrogen lines have very sharp absorption cores, superposed on broad underlying hydrogen lines, and emission wings may also be observed. A good example of this is illustrated in Fig. 4. The absorption lines of ionized metals tend to be sharp.

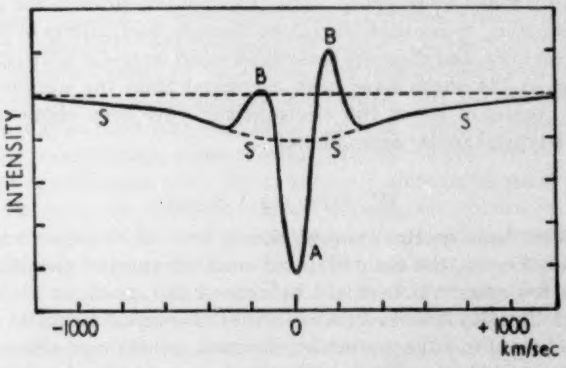


Fig. 4.—*Profile of the Hβ line in the shell star 48 Librae in 1953. The underlying star has an apparent velocity of rotation of about 400 km/sec. For explanation of notation see Fig. 5.* (*Adapted from A. B. Underhill,* Pub. Dom. Ap. Obs. **9**, 363, 1953.)

He I lines are mostly weak and diffuse, but some lines of He I (λ3888 and λ3965) may be strong and narrow. The broadened lines of hydrogen and other elements are produced in the atmosphere of a rapidly rotating star (Fig. 5). The emission, if present, arises in a shell of gas; the narrow absorption cores of the hydrogen lines and the sharp lines of He I and the ionized metals arise by the absorption of photospheric light by that part of the shell which lies in the line of sight.

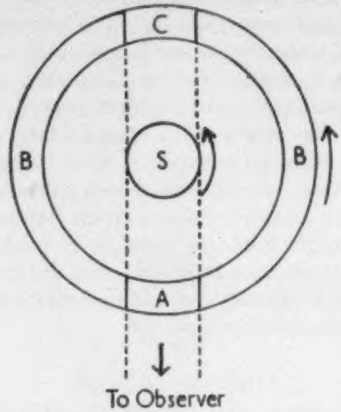


FIG. 5.—*Origin of complex line profiles in shell stars. The star S rotates rapidly, producing very broad absorption lines (SSSS in Fig. 4). The shell rotates relatively slowly. Light from the star passing through the shell at A gives rise to a central absorption feature (A in Fig. 4). The shell itself emits light, and that from the regions B appears as emission wings (B in Fig. 4) bordering the central absorption.*

Because of the distance of the shell from the star the shell must be rotating more slowly than the stellar surface, and in any case only a small part of the shell intercepts starlight in the line of sight, so that lines produced in the shell are not appreciably broadened by rotation. The degree of ionization in the shell is lower than that in the star. Some shell stars show changes, particularly in the intensities of any emission lines, and there are sometimes small irregular fluctuations in light. The densities in the shells have been estimated from the number of Balmer lines visible; values of 10^9 to 10^{13} electrons/cm^3 have been obtained, compared with 10^{15} in a typical stellar atmosphere.

IV. Peculiar A Stars

Most A stars have spectra showing strong lines of hydrogen and very weak metallic lines. During the early Harvard work on spectral classification it was found that a few stars which would be classed as type A on the basis of the hydrogen and Ca II(K) lines had metallic lines of unusual strength. Sometimes these lines belonged to a few particular elements, manganese, silicon, europium, chromium or strontium. These stars became generally known as peculiar A stars. Later other peculiarities of these stars were observed, and they were subdivided into spectrum variables, magnetic stars, and so on. In some stars the strengthening of the spectrum lines was not confined to one or two particular elements, but nearly all lines of all the metallic elements were strengthened. These stars are known as metallic-line stars.

(*a*) *Peculiar A stars.*—As mentioned above, these are distinguished by the abnormal strengths of the lines of some (ionized) elements, other lines having normal intensities. For example, α Andromedae shows strong Mn II lines, and has been called a "manganese star", θ Aurigae shows enhanced Si II, γ Equulei shows enhanced Sr II and 78 Virginis shows enhanced Cr II and Eu II. Peculiar

A stars first appear at about type B8 or B9, and extend throughout type A and into type F as far as F2; at least 10 per cent of all A stars are peculiar. The enhancements of the spectral lines are certainly not due to high luminosity. The absolute magnitudes of the stars are fairly well known; they are slightly above the main sequence. They can occur in galactic clusters and as components of binary systems. Some peculiar A stars are spectrum variables; many others appear not to vary. For example, in HD 125248 lines of Eu II and Cr II vary out of phase with a period of 9·3 days; Cr I and Cr II vary together, so do Eu II and Eu III. The rest of the spectrum is invariable. Many spectrum variables show light variations, with amplitudes of two-tenths of a magnitude or less; phase relationships between light and spectra are different for different stars. It has often been thought that the peculiar line intensities are due to abundance anomalies. This has recently been demonstrated by E. M. Burbidge and G. R. Burbidge, who analysed the spectrum of α^2 Canum Venaticorum and HD 133029. They conclude that calcium is underabundant by a factor of 30, that manganese, chromium, strontium and other metals are overabundant by factors of 5 to 25, and that the rare earths (La, Ce, Pr, Nd, etc.) are overabundant by a factor of 600 on the average. Although there are difficulties in these abundance determinations the differences from normal solar abundances are so large that their reality can hardly be in doubt.

The most important discovery relating to peculiar A stars was made by H. W. Babcock in 1947. He showed that some peculiar A stars have intense magnetic fields in their atmospheres, and he devised an analyser which can measure these fields by means of the Zeeman effect. In his 1958 catalogue Babcock records attempted observations of the Zeeman effect for a selected list of 338 stars. 89 of these have sharp spectral lines and show magnetic fields, 61 have sharp lines and show no evidence of magnetic fields as great as 500 gauss. 66 stars have broader lines and show some evidence of Zeeman effect, 122 have lines too broad to permit Zeeman measurements. All the sharp-line peculiar A stars examined showed magnetic fields; all the magnetic fields are variable to a greater or lesser extent, some showing reversal of polarity. The magnetic variations are synchronous with the spectrum variations in periodic spectrum variables. There is no adequate theory of magnetic fields in stars. The consensus of opinion is that the fields arise in localized regions of the stellar surfaces rather than as general fields. It is not clear to what extent the observed variations of the magnetic fields are related to the rotation and other properties of the stars. It has been suggested that the anomalous abundances are the products of nuclear reactions proceeding in the surface layers of the stars. Such reactions are not possible in normal stars, but in the presence of strong magnetic fields particles may be accelerated to high energies and nuclear reactions become possible.

(*b*) *Metallic-line stars.*—These stars show a well-developed metallic-line spectrum which is a good match for a late A or an early F star, hydrogen lines which are slightly stronger than expected on the basis of the metallic lines, and a Ca II (K) line very much too weak for the spectral type indicated by the other metallic lines. The Ca II (K) line corresponds in strength to a normal early A type star. The metallic lines probably give the best indication of temperature; the equivalent spectral type from the metallic lines corresponds to the observed colour indices. About 100 of these stars are known outside clusters, and in

addition about 30 are members of galactic clusters. Among the brighter metallic line stars may be mentioned Castor B, δ Capricorni and ζ Ursae Majoris B. The stars have absolute visual magnitudes of about $+1$ or $+2$, they lie slightly above the main sequence in the Hertzsprung–Russell diagram. Detailed studies of high dispersion spectra of metallic-line stars have been made by J. L. Greenstein and others, and there are apparent abundance anomalies of scandium, sodium, calcium, strontium and zinc. No satisfactory explanation of these abnormalities has yet been found. Seven metallic-line stars are known to possess magnetic fields which seem to be irregularly variable. In others no field is seen. It is not yet clear to what extent the peculiarities of the metallic-line stars are due to physical conditions (including magnetic fields) and whether we must postulate surface nuclear reactions as the cause of abundance anomalies.

V. White Dwarfs

It is not certain whether one should regard the white dwarfs as peculiar stars, for they may be a perfectly normal stage in stellar evolution. But their spectra do not fit into the normal sequences of dwarf, giant and supergiant, and for that reason they are included in this article under the heading of peculiar stars.

White dwarfs are both apparently and intrinsically faint, and so are hard to observe. The first white dwarf to be discovered spectroscopically was 40 Eridani B, found by W. S. Adams in 1914; Adams demonstrated the white dwarf nature of Sirius B in 1915 and van Maanen found a third in 1917. Others were subsequently found by searching among stars of large parallax or large proper motion; some have recently been discovered using three-colour photoelectric photometry. By 1939 some 18 were known, and the total known in 1958 was about 200, of which about 80 are well-observed. A number of white dwarfs occur in binary systems (the best known being Sirius B) and there is one binary, LDS 275, in which both components are white dwarfs. In spite of their name the white dwarfs in fact cover a range of colour, in the photoelectric system of Johnson and Morgan from $B-V=-0{\cdot}2$ to $+0{\cdot}6$; redder white dwarfs are very difficult to find. Their $U-B$ colour indices are mostly much more negative than ordinary main sequence stars of the same $B-V$ colour, that is, they show an apparent excess of ultraviolet radiation. Absolute magnitudes have been obtained for some white dwarfs directly from their trigonometric parallaxes, for others statistically from their proper motions. The absolute visual magnitudes vary from $+10$ (for colour index $B-V=-0{\cdot}2$) to $+14$ (for $B-V=0{\cdot}6$).

Many white dwarf spectra show only very broad hydrogen lines, broader and stronger than ordinary dwarf A stars. Some of the bluer stars show He I lines, and the hydrogen lines in these are usually relatively weak. The redder white dwarfs often show lines of Ca II, Mg I and Fe I, and little else. Some white dwarfs of various colour indices show continuous spectra, apparently devoid of all lines; the conclusion is inescapable that these are hydrogen-poor stars. There are many other spectral peculiarities in white dwarfs; the observations of Greenstein have shown how many strange features remain to be explained. There must be parameters other than temperature and pressure affecting the spectra; probably the abundance ratios of hydrogen, helium and metals are involved.

Estimates of the surface temperatures of the white dwarfs have been made

from their colours, and the derived values range from 5 000 °K to 20 000 °K. Combining these with the absolute magnitudes of the stars leads to estimates of the radii; they range from 0·006 to 0·024 solar radii, or about 0·6 to 2·5 Earth radii. The masses of three white dwarfs are known from binary star orbits: Sirius B 0·98$\odot$, Procyon B 0·4$\odot$ and 40 Eridani B 0·43$\odot$. The average value of the observed radii is 0·013 solar radii; combining this with the theoretical mass–radius relation yields an expected average mass of 0·56 solar masses, an average mean density of $3{\cdot}5 \times 10^5$ gm/cm^3 and a central density (based on theoretical models) of $2{\cdot}6 \times 10^6$ gm/cm^3, or say 40 tons per cubic inch. The discovery of the existence of these enormous densities was a major surprise in astrophysics.

The theoretical explanation of the structure of the white dwarfs represents a triumph of statistical mechanics. The introduction of the correct quantum theoretical statistics (Fermi–Dirac Statistics) into statistical mechanics in 1926 led R. H. Fowler to a theory of the white dwarfs. He showed that under the conditions prevailing in white dwarfs quantum theory leads to a behaviour of matter very different from that of ordinary gases under laboratory conditions. The matter becomes *degenerate*, and obeys an equation of state different from the ordinary gas laws. The theory has been developed in great detail, especially by Chandrasekhar. There are two main results of the theory. Firstly, there is (in the limiting case of complete degeneracy), a unique relation between the mass of a white dwarf and its radius. Secondly, there is an upper limit to the mass of a completely degenerate star. The observed masses and radii mentioned above are in good agreement with the mass–radius relation provided that it is assumed that their interiors are devoid of hydrogen. Accepting this, the maximum mass of a white dwarf predicted by the theory is 1·4 solar masses. The known white dwarf masses are well below this limit. This limit has an important bearing on theories of stellar evolution. Many of the heavier stars formed early in the life of the Galaxy have burnt themselves out. It is not certain what has been their fate, but if they have become white dwarfs, they must have undergone a substantial loss of mass at some evolutionary stage. Little is known of the processes by which this could happen. When once the stars have become white dwarfs, they can have no remaining nuclear energy sources, and they probably radiate by cooling. Their low luminosity indicates that cooling is a slow process; the redder white dwarfs are clearly very long lived, and may indeed be almost as old as the Galaxy. The problem of Sirius may also be mentioned. Sirius A is a young star; Sirius B is a white dwarf. If Sirius B has evolved from a main-sequence star of the same age as Sirius A it must have been more massive than Sirius A; Sirius B is now less massive than Sirius A, and must therefore have lost mass. This is further evidence for the loss of mass from stars during their evolution.

White dwarfs are of interest in the testing of the theory of relativity. Einstein predicted that light from a star would be red-shifted by a calculable amount compared with the laboratory wave-length. The classical case is Sirius B, for which agreement between theory and observation has been claimed, but for which the observations are difficult. Recent observations of 40 Eridani B yield a red-shift, in velocity units, of $+21(\pm 4)$ km/sec. Einstein's theory, with the best available values of the stellar mass and radius, predicts $+16$ km/sec The agreement is as good as we can reasonably expect.

VI. Carbon Stars

Carbon stars were discovered early in the development of stellar spectroscopy. Secchi in 1866 outlined the first system of spectral classification; his classes III and IV were red stars, the former with flutings shaded to the red and the latter with flutings shaded to the violet. The former are now classed as M or S stars and the latter as carbon stars. The carbon stars were classed as types R and N in the Henry Draper system and these types are still in general use, although more recently use has been made of a C classification due to P. C. Keenan and W. W. Morgan. Carbon stars show strong bands of C_2, CH and CN, and TiO and ZrO are generally invisible. Bands of NH are also present. A famous group of band-heads at $\lambda 4050$, also present in comets, has been shown to be due to triatomic C_3, a linear molecule. This identification was made by examining the bands produced by a mixture of the carbon isotopes C^{12} and C^{13}; there are six possible types of linear triatomic molecule C_3 which can be formed from mixed carbon isotopes, and the $\lambda 4050$ bands have precisely six heads, as required if their origin is C_3. There is another set of bands in the blue-green spectral regions; these long resisted identification, but recently B. Kleman has suggested that they are due to SiC_2. One of Kleman's spectrograms is reproduced on Plate 23 (A).

All the carbon stars so far discovered are either giants, or in a few cases supergiants; no dwarf carbon stars are known. The mean visual absolute magnitudes have been determined from radial velocities and proper motions, values of $-0{\cdot}5$ and $-1{\cdot}8$ being obtained for classes R and N respectively. Many carbon stars are long-period or irregular variables.

An important feature of the spectra of some carbon stars is the occurrence of the isotope C^{13} of carbon. This isotope was first identified in 1929 by R. F. Sanford, who showed that a band head at $\lambda 4744$ was due to the diatomic molecule $C^{12}C^{13}$, the molecule $C^{12}C^{12}$ producing a band head at $\lambda 4737$. D. H. Menzel found a weaker band at $\lambda 4752$ and identified it as due to the molecule $C^{13}C^{13}$. It was at once apparent that the bands involving C^{13} were stronger in many stars than they were in the laboratory, and presumably C^{13} must be more abundant relative to C^{12} in these carbon stars than in terrestrial carbon samples. Many isotopic analyses of terrestrial carbon samples have been made, and an average ratio $C^{12}/C^{13} = 90 \pm 2$ has been found, with occasional variations of a few per cent; none has been found with a much smaller value of this ratio. Searches for C^{13} in the solar atmosphere have proved unsuccessful; the conclusion is that $C^{12}/C^{13} \geqslant 36$. A. McKellar studied many carbon stars, and for twelve for which the analysis could be made found a mean ratio $C^{12}/C^{13} = 3{\cdot}4$. Still more surprising, however, was his result that not all carbon stars showed the C^{13} isotope, and for three stars $C^{12}/C^{13} \geqslant 30$, 60 and 70. Among these, HD 182040 shows other peculiarities (see Section IX) and the others are CH stars (see Section XIV (*b*)).

The immediate cause of the spectral peculiarities of the carbon stars is undoubtedly the presence of an unusually high carbon/oxygen ratio. In M stars carbon is less abundant than oxygen. Most of the carbon is used up in forming the stable and astrophysically unobservable CO molecule, and surplus oxygen is available for the production of TiO. In the carbon stars carbon is probably more abundant than oxygen; all the oxygen is used up in forming CO and surplus carbon is available for the production of C_2, CH and CN. One cannot conclude that all the carbon stars have the same carbon/oxygen ratio; this

ratio probably has a range of values in different stars. The origin of the excess carbon is not understood; C^{12} may be produced by helium burning in a hydrogen-deficient core, but this is a possible explanation only if a mechanism can be found for transporting the carbon to the outer parts of the star. The abundant presence of the C^{13} isotope further requires that the material must have undergone a carbon–nitrogen cycle subsequent to the production of the excess C^{12}.

VII. S Stars

The classification S was introduced by P. W. Merrill and standardized by the International Astronomical Union in 1922 as an addition to the then existing Henry Draper classification. A number of stars were known which broadly resembled M stars, but in which zirconium oxide bands were more prominent than those of titanium oxide. Stars are known with various relative strengths of TiO and ZrO, and there may even be a continuous sequence of stars ranging from S to M. In the best examples of S stars the ZrO bands are stronger than the TiO bands. A typical S star is π^1 Gruis. Many S type stars are long-period variables, including R Andromedae and R Geminorum. More than a hundred S type stars are known, but only a few have been studied in detail. In addition to ZrO and TiO, bands of YO, LaO and SiH are present in S type spectra. Some absorption lines are enhanced relative to K or M stars, for example Ba II, Sr I, Sr II, Zr I, Y II, and many of the lines of the rare earths also show enhancement. No trigonometrical parallaxes are available, and the spectral peculiarities render application of the normal spectroscopic luminosity criteria hazardous. No interstellar lines are visible because of blending with star lines. M. W. Feast showed that π^1 Gruis had a normal companion star which, if the pair was a real physical double, led to an absolute magnitude of the S star between -1 and 0. P. C. Keenan studied the proper motions of 17 S stars and obtained a mean absolute magnitude of -1. It thus seems that S stars are normal giants; no supergiant or dwarf S stars have yet been discovered. S stars seem to be less frequent than carbon stars, but this may be partly because they are harder to recognize; they form a low velocity group and have a galactic distribution similar to carbon stars.

Perhaps the most remarkable discovery concerning S stars was made by P. W. Merrill in 1951. Element number 43 in the Periodic Table was first identified in 1937 as an artificial product of neutron bombardment of molybdenum and it was named technetium. No completely stable isotope is known; the most nearly stable has a half-life of 200 000 years. It had not been found in nature up to 1951. Merrill found the three strongest lines of neutral technetium in the spectra of R Andromedae, R Geminorum and other S stars. The lines can be seen in the spectrum of R Andromedae on Plate 23 (B). This identification must be considered well-established, and we must seek an explanation.

The range of relative strengths of ZrO and TiO in S and M stars prompts the question whether a range of physical conditions alone are a sufficient explanation. Dissociation theory has been applied to this problem, and although some part of the variations in line and band intensities may be due to differing physical conditions it seems as if we must look to real variations in the chemical abundances of zirconium, technetium and the rare earths to provide an adequate explanation. Processes have been suggested which enable these heavier elements to be built up from elements not heavier than iron by means of successive neutron-captures and beta-decays.

VIII. Symbiotic Stars

Symbiotic stars were named and have been discussed extensively by P. W. Merrill. The study of these stars really began with the work of H. H. Plaskett on Z Andromedae. Spectrograms of this star taken at Victoria showed the presence of high-excitation emission lines of the kind found in gaseous nebulae superposed on a continuum at the relatively low temperature of 5200 °K. Subsequently Hogg and Merrill identified bands of TiO in the spectrum. This feature—the superposition of a high-excitation emission line spectrum on a low temperature absorption spectrum—is the essential characteristic of symbiotic stars, and explains the term *combination spectra* applied to their spectra.

A recent catalogue by Bidelman lists 23 of these stars. They include Z Andromedae, R Aquarii, CI Cygni, BF Cygni, AX Persei and AG Pegasi. The emission lines generally include hydrogen, He I, He II, Fe II, Si II, and other permitted lines, such forbidden lines as [O III], [Ne III], [Fe II] and [Fe III], and sometimes some highly excited lines, for example [Fe X]. The absorption spectrum includes in addition to TiO all the usual low-excitation metal lines such as Fe I. Many of the symbiotic stars show variations in light (they are named according to the usual variable star system) of an irregular nature; there is evidence in some cases of underlying periods of a few hundred days. Recent three-colour photometry has shown that the $B-V$ (blue-visual) colour indices of these stars corresponds to types G or K, while the $U-B$ (ultraviolet-blue) colour indices correspond to type B. The radial velocities of the stars are also variable. Two symbiotic stars have been shown by H. W. Babcock to have variable magnetic fields.

The simultaneous occurrence of high and low excitation features in these objects suggests that there is considerable stratification of some kind. The most obvious explanation is that the systems consist of an M type giant, probably an irregular variable, together with a hot early type variable companion, both stars being immersed in a large nebulous envelope whose density is intermediate between planetary nebulae and the shells of shell stars. It is, however, by no means certain that the symbiotic stars are binaries. Neither mutual eclipses nor orbital velocities have been extracted from the complexity of light fluctuations and velocity variations; but orbital velocities would be difficult to separate from the velocities of erupting gases, so that failure to detect orbital motion is not conclusive proof of its absence. Another suggested explanation is that symbiotic objects are a single star surrounded by a large distant cool shell of relatively high density (compared to most extended envelopes of stars). In some cases the forbidden line λ4959 of [O III] has been weakened relative to its companion λ5007, and this is thought to be due to absorption by a TiO band-head at λ4957. This implies that the TiO absorption takes place outside the region where the forbidden lines are formed. For the present the symbiotic stars remain very much of a mystery.

IX. Hydrogen-Poor Stars

These are very rare objects, recognized by the very great weakness of hydrogen in their spectra. So few are known that the stars of this group must be considered as individuals.

HD 124448.—This star was discovered by D. M. Popper. No absorption or emission lines of hydrogen are visible, and no Balmer discontinuity is present,

The helium lines are stronger than in any other star, and helium discontinuities are seen in the ultraviolet; the great strength of these helium features suggests great excess of helium in the stellar reversing layer. Other elements (oxygen, carbon, nitrogen, neon, etc.) are present and, apart from the absence of hydrogen and enhancement of helium, the star resembles a B2 dwarf. Even a small amount of hydrogen would render the helium discontinuities invisible, so that a real deficiency of hydrogen seems to be the only possible explanation of the observed spectrum. HD 168476, another star of this type, was found by A. D. Thackeray and A. J. Wesselink. HD 160641, found by W. W. Morgan and discussed by W. P. Bidelman, is also similar to Popper's star; it appears to be still hotter, most nearly resembling an O star. Interstellar lines in its spectrum suggest an absolute magnitude of about -3.

υ Sagittarii.—This star was studied by J. L. Greenstein, and by others. It is roughly similar to an A star, but the hydrogen lines are exceptionally weak, and metallic lines are stronger than normal. Standard astrophysical procedures indicate a real hydrogen deficiency in the atmosphere of υ Sagittarrii. HD 30353, discovered by W. P. Bidelman, is a cooler star, approximately F-type, also showing very weak hydrogen lines and strong metallic lines.

HD 182040.—This is a carbon star, showing strong bands of C_2 and CN but no bands at all of CH. Hydrogen lines are very weak and C I lines are strong. No C^{13} isotope is present. Several other stars of this type are now known. Plate 23 (C) shows the spectrum of HD 182040 compared with that of the normal carbon star HD 156074.

R Coronae Borealis.—This famous variable star and others of the same type have spectra at maximum light resembling F or G supergiants, but they show unusually strong features of C I and C_2 and very weak hydrogen lines. The carbon isotope C^{13} is not present. At minimum light emission lines appear in the spectrum and the absorption lines become very indistinct. This strange apparent veiling of the absorption spectrum has no adequate explanation; in any case no reason for the variability of these stars is known. They appear to be hydrogen-poor carbon stars of high luminosity, but the evidence for real hydrogen deficiency is not so strong as for the other hydrogen-poor stars.

It is very difficult to see how the peculiarities of these stars can be explained otherwise than as a real deficiency of hydrogen in their atmospheres. Yet these stars still seem to be radiating energy at something approaching their normal rate. This implies either that there is still plenty of hydrogen in their interiors or that nuclear reactions are consuming elements other than hydrogen. The latter process seems more probable, and helium burning may be the source of excess carbon and oxygen.

X. Pulsating Stars

It is not possible to discuss variable stars in detail in this article, and we shall confine attention to a few salient points of interest. A large number of variable stars are believed to be pulsating, the disturbance affecting the whole star. It is possible that all stars in the course of their evolution pass through an unstable stage, and that pulsating stars are to be regarded as normal rather than peculiar. The pulsation gives rise to a number of effects not present in other normal stars.

(*a*) *Classical cepheids.*—At maximum light these resemble normal F5 to F8

supergiants; at minimum, they resemble F8–K1 supergiants, the type advancing with increasing period and giving rise to the period–spectrum relation. Emission lines of Ca II are usually visible on the ascending part of the light curve. These probably arise when superheated gases become visible deep in the atmospheres of the cepheids and are caused in some way by the pulsations.

(*b*) *Long-period variables.*—These occur among stars of types M and S and among the carbon stars. Their spectra are broadly similar to the normal stars of these types, but at various phases they show emission lines of hydrogen and other elements. A well-known set of emission lines in χ Cygni (and other stars) near minimum has recently been shown by Herbig to be due to unusual processes in the molecule AlH. Many of the emission lines have superposed absorption components, showing that the emission lines are formed deep in the atmospheres. The most probable suggestion advanced so far to explain the emission lines is that we are seeing the upper part of a hydrogen convection zone beneath the normal photosphere. This explanation fulfils the requirement that the underlying cause of the line emission is more fundamental than the division between the spectral types, M, S, R and N.

(*c*) *β Canis Majoris stars.*—These stars are of spectral types B1 or B2 and are above the main sequence. They show light variations of up to one- or two-tenths of a magnitude and variations in apparent radial velocity. Some stars have variations with one period, in others two periodic variations are superposed; the periods are between 3 and 6 hours. The velocity curves of some β Canis Majoris stars are apparently discontinuous. This might be due to successive mild ejections of layers of the atmospheres, but there are many objections to this idea and no more satisfactory mechanism has yet been proposed.

(*d*) *Semi-regulars and others.*—There are a large number of semi-regular and irregular variables, whose spectra may be types F, G, K or M and whose light variations are not regular. The spectra look somewhat like supergiants, but there are many minor peculiarities.

XI. Exploding Stars

Many stars are known which show sudden outbursts. These range from flare stars and U Geminorum type variables through recurrent and non-recurrent novae to supernovae. A detailed discussion of these objects is outside the scope of this article. It may however be noted that all show emission lines and other spectroscopic peculiarities, and that the spectral features of the brighter supernovae still resist identification.

XII. Miscellaneous

(*a*) *Carbon-poor stars.* HR 885 (= HD 18474) was found by W. P. Bidelman to have an unusual spectrum. No CH or CN bands are visible; other spectral features indicate a spectral type of G5 III, and normal stars of this type do show CN and CH absorption. HR 6791 (= HD 166208) was shown by J. L. Greenstein and P. C. Keenan to share the same peculiarities. These peculiarities are almost certainly to be interpreted as an actual deficiency of carbon in the stellar atmospheres.

(*b*) *Lithium stars.*—In 1941 A. McKellar discovered that the lithium resonance doublet at λ6708 was very strong in the N star WZ Cassiopeiae. This was the first detection of lithium in stars other than the Sun. R. F. Sanford

showed that WX Cygni had strong $\lambda 6708$ and M. W. Feast found that T Arae was a third star of this type. These are the only N type stars showing strong $\lambda 6708$ among about a hundred which have been examined. All the lithium stars show the C^{13} isotope. It is not yet certain whether abnormally low surface temperatures can account for the strength of the lithium lines, but the indications are that this is not possible and we must regard the lithium stars as a group of peculiar carbon stars with abnormally high abundance of lithium. It would appear that there can have been little mixing between the atmospheres and interiors of these stars, because the internal temperatures of the stars are almost certainly high enough to destroy lithium by nuclear reactions.

(*c*) *Intermediate-carbon stars.* The star GP Orionis is an unusual object in which both TiO and ZrO are weak, but which otherwise resembles an S star. It seems probable that this star is intermediate between carbon stars and S stars. If the abundances of carbon and oxygen are comparable the formation of CO molecules (a highly probable process) will remove most of the carbon and oxygen atoms and neither oxides nor other carbon molecules will form. This will lead to low atmospheric opacity and the strengthening of many spectral lines. CY Cygni is another star which may have approximately equal abundances of oxygen and carbon; it is a red star but has no strong absorption bands.

(*d*) *Ba*II *stars.*—In normal stars, lines of BaII increase in strength with increasing luminosity after about type F5, and one may therefore be tempted to suppose that cool stars with strong BaII lines are supergiants. We have seen that the BaII lines are strong in S stars, and the latter are not supergiants, so that BaII must be used cautiously as an indicator of high luminosity. Another small group of stars is now known with enhanced BaII not due to high luminosity. This group, called the BaII stars, most nearly resembles G and K stars. In addition to the enhancement of BaII lines, lines of SrII, YII and of the rare earths are enhanced, C_2 bands may be seen faintly when they are invisible in similar normal stars, and the CH band is enhanced. No technetium is seen, and no ZrO, although atomic zirconium lines are strong. The best example of a BaII star is ζ Capricorni, and others include HR 774 and HR 5058. HR 5058 has a relatively large proper motion, and calculations show that on any reasonable assumption of the space velocity of the star, it is unlikely to be a supergiant. The star is probably a giant. The enhancements in the spectra are probably due primarily to abundance peculiarities. E. M. and G. R. Burbidge showed that the heavier elements from strontium onwards have abundances at least ten times those in normal stars. It is possible that these abnormal abundances are the product of neutron-capture element-building processes.

XIII. Stars Not Intrinsically Peculiar

There is a possibility that a star which is not itself abnormal may develop abnormalities when it suffers interaction with other stars or with nebulosity. Such stars are discussed briefly in this section.

(*a*) *Binary systems.*—There are many binary systems which consist of pairs of normal stars. Among the closer binaries there are to be found a number whose integrated spectra show peculiarities; these systems are nearly all spectroscopic binaries, too close to be separated visually. The observed peculiarity is the occurrence of emission lines in the integrated spectra. These are undoubtedly due to the presence near the stars of streams of gas ejected from

the stars. Considerable progress has been made in this field in recent years; a general review has appeared in *Occasional Notes* and we shall not discuss the matter further in this article.

(*b*) *T Tauri stars.*—These have a distinctive emission-line spectrum of hydrogen, Ca II and selected lines of Fe I, and sometimes forbidden lines of ionized sulphur. Their underlying absorption spectra lie in the range F to M and they are on or a little above the main sequence. They are invariably on or near the edges of obscured regions, and they often illuminate small bright patches of nebulosity. They are all irregular light variables. The T Tauri stars are the largest group of stars associated with nebulosity. There are a number of spectral peculiarities which indicate that the emission lines are produced in an extended region of gas at relatively low pressure. The T Tauri stars are believed to be objects of relatively recent origin; they are present in some of the younger galactic star clusters, when they are usually above the main sequence, and are possibly in a state of rapid evolution towards the main sequence.

(*c*) *Interacting with nebulosity.*—In addition to the T Tauri stars there are other objects which are associated with nebulosity. They are broadly of types A, F, G or K, with luminosities well above the main sequence. Ca II and Hα are often seen in emission; the stars are situated in dark clouds and illuminate small reflection nebulae.

XIV. Population II Stars

Spectroscopic differences between the high-velocity stars and the low-velocity stars were found in 1922 by B. Lindblad. The subsequent development of the concept of the two stellar populations has led to correlations between the properties of the stars. Most high-velocity stars are members of Population II. The earlier types (roughly equivalent to normal Population I A, F and early G types) of Population II stars show a general weakening of metallic lines in their spectra. The later G and K giants show weakening of the CN bands. Among the stars of Population II are a number of distinct groups which will be discussed separately.

(*a*) *G–K giants.*—The spectra of Population II giant stars of types G6 to K4 show a weakening of the CN bands; those of somewhat earlier types show a general weakening of atomic lines and a strengthening of CH bands. It is possible that differences in chemical composition are responsible for these peculiarities. M. Schwarzschild, L. Spitzer and R. Wildt suggested that a low abundance of metals relative to hydrogen in Population II stars could explain the peculiarities in G–K giants. A reduction in the metal/hydrogen ratio by a factor of three is required, together with a reduction by a factor two in the (carbon + oxygen + nitrogen)/hydrogen ratio. Most of the brighter stars in globular clusters show similar peculiarities to an even greater degree than nearby high-velocity giant stars; the metallic lines in globular cluster stars are much too weak by comparison with hydrogen lines and colour indices, and a metallic abundance deficiency by a factor ten is required to explain the metallic-line weakness.

(*b*) *Carbon stars* (*CH stars*).—There exist a number of high-velocity carbon stars. Their spectra show very strong CH bands, in line with the behaviour of other high-velocity giant stars. Atomic lines are very weak; even the line Ca I $\lambda 4227$ is inconspicuous in the CH stars. The bands of C_2 and CN are quite strong, although the CN bands may be somewhat weaker than normal carbon

stars. Atomic lines of a few ionized elements (Sr II, Ba II) are strengthened relative to normal carbon stars; this would suggest high luminosity, but other evidence seems to show that the CH stars are normal giants. Their effective temperatures probably range from 3 600 °K to 4 600 °K. There is good reason to think that the appearance of CN, CH and C_2 in the spectra of the CH stars is what would be expected if in any high-velocity star the ratio carbon/oxygen were increased to the amount characteristic of carbon stars. It is interesting to note that among the CH stars there are examples showing the isotope C^{13} and others in which this isotope is not seen.

(*c*) *Subdwarfs*.—These stars were first discovered by Adams from the weakness of certain features in their spectra. The normal stars most nearly resembling the subdwarfs range through spectral types B to K. Subdwarfs of all types show a general weakening of their absorption spectra compared to corresponding normal stars. Subdwarfs of approximate type A have abnormally narrow lines of hydrogen and very weak lines of metals, especially Mg II and Fe II. Those of types F and G have a very weak CH band, and those of later types have a strengthened CN band. Chamberlain and Aller found the atmospheres of HD 19445 and HD 140283 deficient in calcium and iron relative to hydrogen.

Trigonometrical parallaxes are available for some subdwarfs; the visual absolute magnitudes of the subdwarfs are found to fall two or three magnitudes below the main sequence. They appear to be well separated from the white dwarfs if the usually quoted spectral types are accepted. Many of the subdwarfs have high proper-motions and high radial velocities. Most have highly eccentric orbits about the centre of the Galaxy, and during their motions pass quite close to the galactic nucleus. The motion of the Sun relative to the subdwarfs is very high, similar to that relative to the RR Lyrae stars. They form a nearly spherical distribution about the galactic centre.

Many subdwarfs show abnormally negative $U-B$ (ultraviolet minus blue) colours for a given $B-V$ (blue minus visual) colour, that is, they are abnormally bright in the ultraviolet. Miss Roman has suggested that this is due to the general weakness of the metallic lines in the spectrum; she has shown that the ultraviolet excess is especially frequent among subdwarfs with high velocities relative to the Sun. When account is taken of the ultraviolet excess O. J. Eggen and A. R. Sandage have found that the total radiation emitted by a subdwarf (i.e. its bolometric magnitude) is the same as that by a normal star of the same effective temperature. In the $M_{bol} - \log T_e$-diagram there is effectively just one main sequence which includes normal stars and high-velocity subdwarfs.

(*d*) *Faint blue stars*.—A number of hydrogen-poor helium-rich objects have been found among faint blue stars. They show weak hydrogen, strong and broad He I and He II, very strong and sharp N II, N III, Si IV, no C II and weak C III. This strength of nitrogen and weakness of carbon is in contrast to hydrogen-poor stars such as HD 124448 (mentioned above in Section IX) which have strong carbon lines. An example is HZ 44, an eleventh magnitude blue star, probably of luminosity similar to that of the Sun. Another interesting example is B.D. $+28°4211$. Weak interstellar calcium lines indicate an absolute magnitude of $+4$. It has a large proper motion and is almost certainly a high velocity star. These stars are about 8 magnitudes below the main sequence.

(*e*) *Cluster cepheids*.—In general appearance these have spectra similar to

other high-velocity F stars, with metallic lines very weak at maximum light and quite weak at minimum light.

(*f*) *Long-period cepheids.*—These are rather similar to classical cepheid variables, they show a characteristic hump in their light curves and their spectra show bright hydrogen lines during increasing brightness.

Conclusion

In the present article we have given a brief outline of the main types of peculiar stars and we have indicated a few of the most outstanding peculiarities. There are many other peculiarities which have been discovered and studied, and although some have been understood and possible mechanisms for others suggested, many phenomena remain for which no explanation is available. And it is unfortunately true that even in cases where the observable peculiarity has an obvious physical interpretation we are still completely ignorant of the underlying cause of the phenomena. Some progress has been made; more than ever remains to be done before the intriguing peculiarities of the stars are fully unravelled.

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TYCHO BRAHE'S SYSTEM OF THE WORLD

Marie Boas and A. Rupert Hall

Tycho Brahe (1546–1601) was, in his own way, as original an astronomer as Copernicus, though of a quite different turn of mind. Copernicus was primarily a theoretical astronomer, who did indeed make observations (which Tycho discussed with great respect) and who used the observations of others, but who was far from expecting observational astronomy to provide exact measurements to which theory would need to conform. Tycho was first and foremost an observational astronomer; indeed, he recorded that in his youth he had read works on astronomical theory only in order to learn enough to permit him to make useful observations and to reduce these observations into serviceable tables. Yet he came to devise a theory of the universe, the Tychonic system, which for two generations after his death provided an acceptable alternative to the Copernican system as a replacement for the obsolescent Ptolemaic one. Surprisingly, his own account of his system has not before been translated into English; except for the often reproduced diagram (Fig. 1) it has remained hidden in a detailed work on his observations of the great comet of 1577.

Tycho became an astronomer through spontaneous early interest and the pressure of what he called aetherial phenomena. The dramatic appearance in November 1572 of a supernova in Cassiopeia made him, who thought he knew all the major stars in the northern heavens, earnestly endeavour to find out as much as possible about the strange apparition. His determination that this was indeed a new star, and certainly located in the 'aetherial orbs'—that is, in the celestial region beyond the Moon—meant that he at once became an opponent of orthodox astronomy. For Ptolemaic astronomy was based upon Aristotelian physics, which divided the world into two parts: the eternal, unchanging heavens, where lay the stars and planets all moving with perfect—and therefore circular—motion; and the sublunary terrestrial world, the place of generation and corruption and change and straight-line motion. All phenomena of change—meteors, rainbows, comets—belonged to the sublunary world. The new star, if it were indeed new—and its brightness and location in so well known a constellation meant that most observers agreed that it had never been seen before, should, therefore, have been a sublunary phenomenon. But though some astronomers did attempt to classify it as a comet, the observations of Tycho and others showed that it was most probably motionless, and in any case located well beyond the Moon, since the most careful observations could detect no parallax. The heavens were therefore not unchanging; and Tycho, convinced of this fallacy in the Aristotelian cosmology, became ready to adopt further modifications in it, whenever these were required by the observational evidence.

When Tycho observed the spectacular comet of 1577, the first of a series of naked-eye comets which he was lucky enough to witness, his observatory of Uraniborg was well established. The comet, like the supernova of 1572, showed no parallax, and Tycho's instruments and instrumental techniques were now so refined that he was quite certain of the correctness of his observations. The comet must, then, lie in the celestial world, orthodox astronomy notwithstanding,

even though this was bound to lead to theoretical complications. Tycho was prepared to accept this situation, but he knew that he must be very sure of his ground before making his novel views public. Only after ten years did he finally publish his observations, with a critique of the work of other astronomers, in a work whose title was a challenge to orthodoxy; for to call a book *De Mundi Aetherei Recentioribus Phaenomenis** (Uraniborg, 1588), when it discussed a comet, was to indicate the firmness of his conviction about the place in the universe where comets were to be found. The book was intended to be a part of a larger work, *On the Restoration of Astronomy*, which was never completed.

It was because he had to fit the comet's path as computed from his own observations into the region of the planetary spheres that Tycho felt constrained to pause in the middle of his detailed account of cometary observations to explain his conception of the construction of the universe. This is a brief digression, occupying only a part of Chapter VIII of the *Recent Phenomena*, and the detailed account he mentions was never, in fact, attempted. The Tychonic system is therefore only sketched out, and suffers from all the virtues and defects of a cursory treatment. Nevertheless, it clearly presents his intentions, as well as his reasons for rejecting both the established Ptolemaic doctrine—long uncomfortably shaky, having been patched up over the centuries to fit new observations—and the new Copernican system.

The Tychonic system is a necessary consequence of Tycho's discovery that comets were celestial phenomena, for, as he says, in the Ptolemaic system the space above and below the Sun is completely filled by the spheres of the planets, leaving no empty space for the paths of the comets. Tycho seems to have felt from the beginning that comets revolved about the Sun, not the Earth; on either hypothesis there would have to be room for their motion. But if the planets, both inferior and superior, in fact revolved about the Sun, and the Sun with its planetary companions at the same time revolved about the Earth, then, he reasoned, there would be ample space in the region between Venus and Mars for the comets to pursue their paths about the Sun. This is, quite simply, the Tychonic system, which is well displayed in Tycho's own diagram. This system, as Tycho pointed out, shares with the Copernican the great advantage that it explains why the motion of the Sun is always mixed with the apparent motion of each of the planets. Tycho knew, of course, that simple circles by no means explained all the irregularities of the planetary motions; like Copernicus, he was constrained to continue the use of eccentrics, though, like Copernicus again, he was able to dispense with the use of equants†. Tycho never worked out planetary motions in detail; but it is clear that his system is at once both as simple and as complex as the Copernican system, to which it is mathematically equivalent, so that both obviate the same irregularities. Quite astonishingly novel is Tycho's willingness to concede a possible departure from perfect circular motion in the case of comets; for though it is only a tentative suggestion, he does remark that comets might follow an oval, rather than a perfectly circular path.

The one difficulty in the Tychonic system is readily apparent from Figs. 1 and 2: the paths of the inner planets, of comets and of Mars cross the path of the

* *On the Most Recent Phenomena of the Aetherial World.*

† Tycho disliked the equant—a point not at the centre of a circular orbit about which the angular velocity of motion is uniform—just as much as did Copernicus, and for the same reason, that it was not 'harmonious'.

Sun about the Earth. This would be unthinkable if these bodies were carried by solid spheres. But Tycho had already firmly rejected the motion of crystalline spheres; he correctly argued that the spheres ought to be conceived of as mere geometrical constructions, or ways of expressing a circular path, and he preferred to think of the planets as moving in pure circles, without any supporting spheres. As he remarked when evaluating the work of Michael Maestlin (an excellent observational astronomer and a Copernican):

> " For there are not really any Orbs in the Heaven, as from this passage one may gather that Maestlin believes; those which Authors have invented in order to save the appearances exist only in imagination, in order that the motions of the planets in their courses may be understood by the mind, and may be (after a geometrical interpretation) resolved by arithmetic into numbers. Thus it seems futile to undertake this labour of trying to discover a real orb, to which the Comet may be attached, so that they would revolve together. Those modern philosophers agree with the almost universal belief of antiquity who hold it as certain and irrefutable that the heavens are divided into various orbs of hard and impervious matter, to some of which stars are attached so that they revolve with them. But even if there were no other evidence, the comets themselves would most lucidly convince us that this opinion does not correspond with the truth. For comets have already many times been discerned, as the result of most certain observations and demonstrations, to complete their course in the highest Aether, and they cannot by any means be proved to be drawn around by any orb."*

This seems quite clear; but the problem of what kept the planets fixed in their positions in the universe, if they were not attached to material spheres, seems not to have presented itself to Tycho. To Copernicus and other sixteenth century astronomers ' orb ' meant both sphere and circle, and was used in both senses. Tycho follows this usage, as in the passage above where ' orb ' signifies a solid sphere; but in referring to his own system and in his own theory of the motions of comets, he uses ' orb ' to mean a circle, or circular path, indeed almost an ' orbit ' in the modern sense. The sphere of fixed stars, as the diagrams show, he retained, presumably because he could not think of the universe as infinite.

The advantages of the Tychonic system over the Ptolemaic are obvious; they are, in fact, the advantages already displayed by the Copernican system. Why then, one may ask, did Tycho not accept the work of Copernicus, at the same time continuing the Copernican revolution by abolishing solid spheres? His objections to the Copernican theory were those of most competent anti-Copernicans of the day, and they were by no means trivial. Common sense detects the motion of the Sun and the stability of the Earth, and neither scientists nor laymen felt—and rightly—that common sense should be lightly denied. Evidence against common sense was, moreover, lacking; Copernicus could summon no argument in favour of his system except that it made the motions of the heavenly bodies more nearly perfect—that is, circular and simple—as they ought to be according to the tenets of Aristotelian philosophy. This merit

* J. L. E. Dreyer, ed. *Tychonis Brahe Dani Opera Omnia*, t. IV, Copenhagen, 1929, p. 222 (Chapter X of the *Recent Phenomena*).

Tycho preserved, and admired. But the motion of the Earth was rendered impossible by Aristotelian physics, which placed the Earth in the centre of the universe because, unlike the heavenly bodies located outside the spheres of terrestrial elements, the Earth was heavy and therefore, like all heavy objects, sought the centre of the universe. Once there, what should move it? For earth, the element, was naturally sluggish and unapt to motion, very unlikely to be inclined to whirl about either on its axis or through space. Besides all this, Tycho was convinced that if the Earth rotated on its axis, then a stone dropped from the top of a tower would never hit the ground at the foot of the tower. This was a point of great difficulty to the sixteenth century; in the seventeenth century the argument was extended by comparison with the effect of dropping a stone from the masthead of a moving ship. When Tycho spoke of the 'physical absurdity' of the Copernican system it was such points as these which he had in mind. There was, further, a theological absurdity. Tycho was a good Lutheran, and agreed with Luther that Scripture had declared that it was the Sun and not the Earth which Joshua had commanded to stand still. The Earth, therefore, could not normally be moving, or Holy Writ was controverted. Where reason and revelation reinforced one another, what wonder if he were convinced that the Earth must stand still? Especially as his system had disposed of the complexities and irregularities of the Ptolemaic theory.

While firmly denying the reality of the Copernican conception, Tycho always spoke of Copernicus as one of the great astronomers, noteworthy both for his theoretical and his observational contributions. Though he could not accept his ideas, he recognized their quality. Ironically, Tycho's own ideas helped pave the way for an eventual acceptance of the Copernican system, though in a much modified form. When Tycho denied the reality of the material spheres, he helped to destroy the sphere of fixed stars, though unintentionally, and to create an unlimited, if not an infinite universe, quite different from the small, tightly bounded universe Copernicus described. When Tycho placed the path of the comets in the midst of the paths of the planets he contributed to the framework of the Newtonian universe. And it was from Tycho's observations that Kepler deduced that the orbits of the planets were elliptical—as Tycho had once, though very tentatively, suggested that the orbits of the comets might be oval. The Tychonic system thus had an influence outside the group of convinced Tychonians. It is one of the surprises of history that the Tychonic system should have been so widely and quickly accepted, for it was, as can be seen here, very sketchy, and seldom can astronomers have taken seriously a theory worked out in so little detail. This was partly because the Tychonic system filled a need, since it permitted one to dispense with the Ptolemaic absurdities without denying common sense, scientific theory and religious belief. It was also, in part, because the Tychonic system was framed in accordance with what was to become the scientific method more characteristic of the new philosophy of the seventeenth century.

For Tycho had been led to his system through observation. It was the detailed and careful observations of comets which showed him how necessary it was to dispense with solid spheres, and to fit the comets into the planetary system—as his theory did. To his mind, it combined the best of the Copernican and Ptolemaic systems and avoided the disadvantages of both. Besides this, it provided a reason (as the Copernican system of course also did) for the special

character of the Sun. This Tycho glorified as the controller of human and worldly destiny; just as the Sun's warmth and light breathed life into the creatures of the Earth, so it controlled and led the planets in their motions. Here was no mechanical universe, but one informed with life. Tycho's references to the Sun as leader and king of the planetary dance are somewhat conventional—Rheticus used the same phrase in his *Narratio Prima*, the first published account of the Copernican doctrine—but none the less sincere for that. When Tycho came to rewrite the work on the supernova of 1572 he began with a dithyramb on the beauty, majesty, and importance of the Sun, controlling time, animating the terrestrial world and regulating the motions of the planets, whose own motion should therefore be more accurately known, as he somewhat prosaically concluded. This animistic point of view helps to explain why Tycho was so immediately cordial to Kepler, and why Kepler, though a Copernican and a mathematical mystic, could speak with such respect of the Tychonic system in his first book, the *Mysterium Cosmographicum* of 1596. Yet it by no means lessened Tycho's conviction that one must arrive at an astronomical theory through observation. Tycho was indeed a man of his times, and the way in which he combined mysticism, observation, respect for authority and novelty was typical of an age of transition.

What follows is a translation of the first part of chapter VIII of the *Recent Phenomena*, as published in volume IV of J. L. E. Dreyer's edition, *Tychonis Brahe Dani Opera Omnia* (Copenhagen, 1929), p. 155–62. The rest of the chapter is entirely concerned with detailed observations on the comet of 1577 and is not translated here.

Of the discovery of the place or space between the celestial revolutions of the planets, where the comet may fitly run its course, and of the construction of an hypothesis, by which its apparent motion is approximately represented.

Thus from what has gone before it was made obvious and beyond any controversy that our Phaenomenon [the comet of 1577] had nothing in common with the elementary world, but was shown to have a motion in the Aether far up above the Moon, its tail perpetually maintaining an Olympian relationship to certain stars. It remains now, and seems to be especially fitting, that we should assign to it also some particular place in the very wide space of the same Aether, in order that we may establish between which orbs of the Secundum Mobile it will direct its path. Indeed the Aetherial World comprises incredible vastness, so that if we assume that this elementary world [measures] from the centre of the Earth to the nearest limits of the Moon about 52 Earth-radii (each of which contains 860 of our common or German miles) this will be contained 235 times in the rest of the space of the Secundum Mobile, that is to say as far as the extreme distance of Saturn from the Earth. In this enormously vast interval seven planets perform incessantly their wonderful and almost divine periodic motions; so that I can say nothing about that immense distance of the Eighth Sphere, which is beyond doubt greater by far than that of Saturn at his furthest point. On the other hand, according to the Copernican hypothesis, that space between Saturn and the Fixed Stars will be many times greater than the distance of the Sun from the Earth (which however is such that it includes the semidiameter of

the elementary world about twenty times). For otherwise the annual revolution of the Earth in the great orb, according to his speculation, will not turn out to be insensible with respect to the Eighth Sphere, as it ought. Because the region of the Celestial World is of so great and such incredible magnitude as aforesaid, and since in what has gone before it was at least generally demonstrated that this comet continued within the limits of the space of the Aether, it seems that the complete explanation of the whole matter is not given unless we are also informed within narrower limits in what part of the widest Aether, and next to which orbs of the planets, [the comet] traces its path, and by what course it accomplished this. So that this may be more correctly and intelligibly understood, I will set out my reflections of more than four years ago about the disposition of the celestial revolutions, or synthesis of the whole system of the world. These were referred to before, but postponed to this point in the Astronomical Work, where they are required.

I considered that the old and Ptolemaic arrangement of the celestial orbs was not elegant enough, and that the assumption of so many epicycles, by which the appearances of the planets towards the Sun and the retrogradations and stations of the same, with some part of the apparent inequality, are accounted for, is superfluous; indeed, that these hypotheses sinned against the very first principles of the Art, while they allow, improperly, uniform circular motions not about [the orbit's] own centre, as it ought to be, but about another point, that is an eccentric centre which for this reason they commonly call an equant. At the same time I considered that newly introduced innovation of the great Copernicus, in these ideas resembling Aristarchus of Samos (as Archimedes shows in his *Sand-Reckoner*), by which he very elegantly obviates those things which occur superfluously and incongruously in the Ptolemaic system, and does not at all offend against mathematical principles. Nevertheless the body of the Earth, large, sluggish and inapt for motion is not to be disturbed by movement (especially three movements) any more than the Aetherial Lights are to be shifted, so that such ideas are opposed to physical principles and also to the authority of Holy Writ which many times confirms the stability of the Earth (as we shall discuss more fully elsewhere). Consequently I shall not speak now of the vast space between the orb of Saturn and the Eighth Sphere left utterly empty of stars by this reasoning, and of the other difficulties involved in this speculation. As (I say) I thought that both these hypotheses admitted no small absurdities, I began to ponder more deeply within myself, whether by any reasoning it was possible to discover an hypothesis, which in every respect would agree with both Mathematics and Physics, and avoid theological censure, and at the same time wholly accord with the celestial appearances. And at length almost against hope there occurred to me that arrangement of the celestial revolutions by which their order becomes most conveniently disposed, so that none of these incongruities can arise; this I will now communicate to students of celestial philosophy in a brief description.

I am of the opinion, beyond all possible doubt, that the Earth, which we inhabit, occupies the centre of the universe, according to the accepted opinions of the ancient astronomers and natural philosophers, as witnessed above by Holy Writ, and is not whirled about with an annual motion, as Copernicus wished. Yet, to speak truth, I do not agree that the centre of motion of all the orbs of the

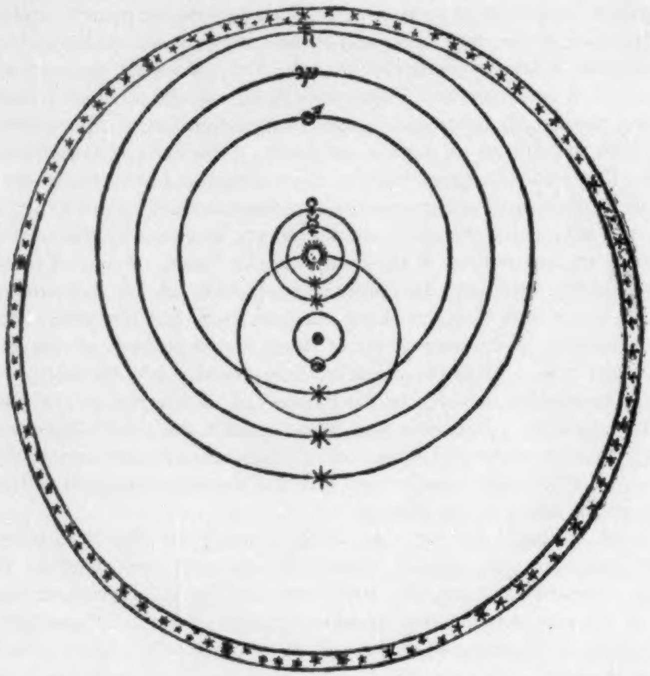
Secundum Mobile is near the Earth, as Ptolemy and the ancients believed. I judge that the celestial revolutions are so arranged that not only the lamps of the world, useful for discriminating time, but also the most remote Eighth Sphere, containing within itself all others, look to the Earth as the centre of their revolutions. I shall assert that the other circles guide the five planets about the Sun itself, as their Leader and King, and that in their courses they always observe him as the centre of their revolutions, so that the centres of the orbs which they describe around him are also revolved yearly by his motion. For I have found out that this happens not only with Venus and Mercury, on account of their small elongations from the Sun, but also with the three other superior planets. The apparent inequality of motion in these three remoter planets, including the Earth, the whole elementary world and at the same time the confines of the Moon in the vastness of their revolutions about the Sun, which the ancients accounted for by means of epicycles, and Copernicus by the annual motion of the Earth, is in this way most aptly represented through a coalescence of the centres of their spheres with the Sun in an annual revolution. For thus as suitable an opportunity is offered for the appearance of the stations and retrogradations of these planets and of their approach to and recession from the Earth and for their apparent variations in magnitude and other similar events, as either by the pretext of epicycles or by the assumption of the motion of the Earth. From all these things, when the former treatment by epicycles is understood, are deduced the lesser circuits of Venus and Mercury about the Sun itself, but not around the Earth, and the refutation of the ancient views about the disposition of epicycles above and below the Sun. Thus a manifest cause is provided why the simple motion of the Sun is necessarily involved in the motions of all five planets, in a particular and certain manner. And thus the Sun regulates the whole Harmony of the Planetary Dance in order that all the celestial appearances may subject themselves to his rule as if he were Appollo (and this was the name assigned to him by the ancients) in the midst of the Muses.

So much, indeed, for the rest of the more particular differences of the apparent inequality [of motion], which the ancients conceived to be represented by eccentrics and equants, and Copernicus by an epicycle on the circumference of the eccentric, having the same angular velocity. These [differences] can also easily be represented in our hypothesis, either by a circle of a sufficient size in an eccentric orb about the Sun, or by a double circle in some concentric orb. Thus [in our system] no less than in the Copernican, all circular motions take place with respect to their own centre, since we have rejected Ptolemaic disorder. The manner of this we shall explain more particularly and fully in the work on the restoration of astronomy which (God willing) we have decided to elaborate. There we specifically discuss this hypothesis of celestial motions and shall demonstrate both that all the appearances of the planets agree perfectly among themselves and that these more correctly correspond [with our hypothesis] than with all others hitherto employed. So that this our new invention for the disposition of the celestial orbs may be better understood, we shall now exhibit its picture [Fig. 1].

I have, in truth, constructed a fuller explanation of the new disposition of the celestial orbs, in which are important corollaries of all the present cogitations. I shall add this near the end of the work, and there it will be shown first of all from the motions of comets, and then clearly proved, that the machine of Heaven

is not a hard and impervious body stuffed full of various real spheres, as up to now has been believed by most people. It will be proved that it extends everywhere, most fluid and simple, and nowhere presents obstacles as was formerly held, the circuits of the planets being wholly free and without the labour and whirling round of any real spheres at all, being divinely governed under a given

A new hypothesis of a world system newly invented by the author, which excludes both the redundancy and awkwardness of the Ptolemaic system, and the recent physical absurdity of Copernicus in [postulating] the motion of the Earth, and in which all things correspond most conveniently with the celestial appearances.



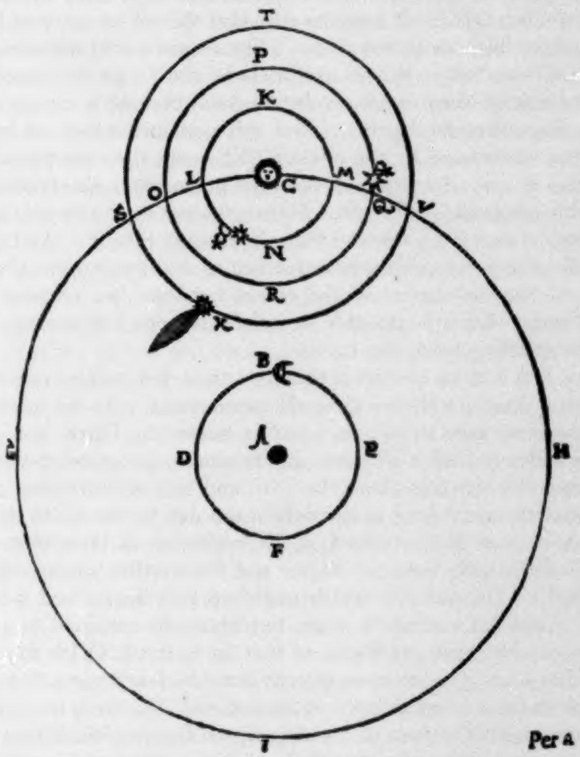
AA 3 **Pleniorem**

[Fig. 1.]

law. Whence also it will be established that no absurdity in the arrangement of the celestial orbs follows from the fact that Mars in opposition is nearer to the Earth than the Sun itself. For in this way there is not admitted any real and incongruous penetration of the orbs (since these are really not in the sky, but are postulated solely for the sake of teaching and understanding the business) nor can the bodies of any of the planets ever run into one another nor for any reason disturb the harmony of the motions which each of them observes. So that the imaginary orbs of Mercury, Venus, and Mars are mixed with that of the Sun, and cross it, as will be more clearly and extensively declared in that place near (as I said) the colophon of the whole book, especially in our astronomical volume where we deal explicitly with these things.

Now, however, we shall borrow at least that part from this same new scheme of the aethereal revolutions, which satisfies for the moment the difficulty in alloting a place for this comet, and providing an hypothesis to facilitate the ordering of its appearances.

The basis for these celestial revolutions having been laid down, I say that everything most aptly agrees with the apparent motion of this comet, if we understand that it also, as if it were an adventitious and extraordinary planet, has, no less than the other planets, revealed that the centre of its revolution is in the Sun.



[Fig. 2.]

It has traced about this centre that portion of its own sphere by which it goes beyond not only the Sphere of Mercury, but even that of Venus; for it can depart from the Sun a sixth part of the heavens, while Venus is elongated not much more than an eighth part. Indeed, the comet proceeded in this orb in such a way that if it is assumed to be at the lowest parts of it orb and nearest to the Earth when it was joined to the mean motion of the Sun, it may be allowed to have proceeded thence in the order of the Signs [Eastward] toward the apogee of its orb, otherwise than occurs with Venus and Mercury, the constant centre of this revolution agreeing with the simple motion of the Sun. To perceive all these things rightly, we must now submit to the eyes a suitable arrangement of the construction of the orbs [Fig. 2].

By A is understood the globe of the Earth located in the centre of the universe, closest to which revolves the Moon in the orb BEFD, in which all the region of the elements is contained. That the comet can in no way be discovered between these bounds of the Lunar orb was, however, sufficiently demonstrated by us in the Sixth Chapter. Above this let CHIG be the annual orb of the Sun revolving about the Earth, in which the Sun is represented near C, upon which are located the centres of all the orbs of all the rest of the 5 planets, according to our renovation of the celestial hypothesis. And since the star of Mercury revolves closest to the Sun in the orb LKMN and a little above this the star of Venus revolves in the orb OPQR, it happens fitly that the comet revolves in yet a little greater orb described about the Sun. [The comet's orb] includes the orbs of Mercury and Venus only; it does not [include] the Lunar orb together with the Earth (as the star of Mars on its revolution does) because it cannot digress from the Sun by more than 60 degrees. And this same orb which we impute to the comet may be understood by the circle STVX, with the comet itself near X, in which sitation it was when seen at the time of our first observation. It has a motion in this orb in the order of the Signs, contrary to the revolutions of Venus and Mercury, so that it goes round from X through S to T. And the centre of the same orb observes it simple motion allied to the Sun perpetually. And this disposition of the revolution of the comet between the celestial orbs being accepted, I assert that it is possible to satisfy its apparent motion, as it is perceived by us dwelling on A, the Earth.

However, this is to be observed, that the comet, led in this same circular path about the Sun, does not always show the same speed. At the beginning, when located in the lower part of its orb, which is nearer the Earth, it is moved more slowly; thereafter indeed it will increase its motion more and more, and this in such a manner that whereas about the IXth and Xth of November it completed barely ten twelfths of a degree in its circle in one day, by the XXth it completed a whole degree in each day. Indeed, at the beginning of December it increased its motion little by little from one degree and five twelfths until in the first days after the XXth of December it was brought up to a degree and a half, beyond which limit it did not extend its haste, but gradually returned to a slackening. All the same, its variation was slight, so that up to the XXVIth day of January, when it was last seen by us, no more than five twenty-fourths of a degree had been lost from the one and a half degrees of its motion. For there was about the end of January once again a motion of one degree and five twelfths during the natural day, in the same measure as for the whole of December and January; that is, it did not alter its daily progress, except at the most five twenty-fourths. So little in so long a time did its revolution about the Sun deviate from perfect equality. Indeed, in November it made from day to day generally more, by a little quicker variation; and all these things may be seen more fully from the fourth row of its table, which we shall subjoin to the end of the following chapter*.

Indeed, I show, as may be more convenient, that the comet in its own orb through the whole of its duration completes an equal arc in an equal interval of

* p. 177 (Dreyer's edn.). The table shows that about the beginning of November the 'Daily motion of the comet in its orb' during each 24 hours was 0° 55′ to 0° 58′; by November 11–20 it was 1°, increasing thereafter by irregular jumps to a maximum of 1° 30′ about the winter solstice; it then decreased its velocity, and from January 25–26 it moved 1° 25′. The greatest change was at the end of November, when the daily motion increased by 25′ in one week.

time. For thus a simple uniformity of revolution is more rightly preserved, namely with that same regularity by which the planets themselves constantly observe a perpetual equality in their circuits. And this permits the inequality of the comet which occurs in its own circumgyrations to be bounded and corrected; by twisting the centre of its orb about the Sun circularly and in a due proportion in the opposite direction, or by adding to the circular circumference of the same, the motion may be now inhibited, now released. Nevertheless, because this business acquires through such complexities more obscurity and involvement than light and clarity, I was unwilling to bring up the third intricate arrangement of the various motions for an equal degree of consideration, especially as it would be very inappropriate to make such quickly vanishing bodies as comets liable to follow artificially compounded and much involved curves of motion. And so I choose to retain those daily paths of the comet in its orb about the Sun which experience itself so abundantly supplied, notwithstanding that at the beginning they were a very little slower, and soon after this returned more quickly in each successive passage; especially when through the greatest and longest time of their visibility, they conformed to a nearly constant equality. For in December and January, for two whole months, the motion did not vary from equality by more than five twenty-fourths (as I indicated before) which truly is very little and almost of no moment; in November alone, and at most for half the month, it admitted a sensible alteration; so that only about one fifth part of the whole duration was subject to inequality, for the four remaining ones were almost exempt from it.

Nor is it the case that anyone may think that our hypotheses are to be overthrown because of the short duration or great inequality of the motion. For it is probable that comets, just as they do not have bodies as perfect and perfectly made for perpetual duration as do the other stars which are as old as the beginning of the world, so also they do not observe so absolute and constant a course of equality in their revolutions—it is as though they mimic to a certain extent the uniform regularity of the planets, but do not follow it altogether. This will be clearly shown by comets of subsequent years, which will no less certainly be located in the Aethereal region of the world. Therefore either the revolution of this our comet about the Sun will not be at all points exquisitely circular, but somewhat oblong, in the manner of the figure commonly called ovoid; or else it proceeds in a perfectly circular course, but with a motion slower at the beginning, and then gradually augmented. However this may be, the comet in fact revolves around the Sun just the same, even though with a certain inequality, which yet is not confused or irregular.

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